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FAILURE ANALYSIS OF HELIOCOPTER EXTERNAL CARGO-HANDLING SYSTEMS

Robert E. Hunt

Arthur D. Little, Incorporated

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The data were taken primarily from cargo helicopters deployed in Vietnam. Their overall utilization, load categories, and rigging materials were determined, and a consensus summary of the cause of specific failures was compiled and documented.

A data analysis was conducted with the relationship of failure occurrences and rates determined for specific types of accidents and failures. Predominant causes of failures were analyzed, a cost/value of relationship of cargo dropped established, and projections of the heavy-lift helicopter as a cargo carrier were made.

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U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

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This report was prepared by Arthur D. Little, Inc., under the terms of Contract DAAJ02-72-C-0063. The original intent of the program was to gather documented data on helicopter external cargo handling system failures, to analyze this data with regard to cause of failure, and to develop and recommend cost-effective corrective actions that would significantly attenuate failures in external cargo-carrying operations.

Early in the program, it became apparent that the volume of documented data available was entirely insufficient to perform the detailed, quantitave type of failure analysis desired. Because of the highly desirable and valuable nature of the program, Arthur D. Little was instructed to reorient its approach along more qualitative lines and to continue with the program. As a result, the contractor relied heavily on qualitative information gathered through numerous interviews with Army personnel familiar with the problem.

This report is considered to provide a valuable insight into the problems that plague helicopter external cargo-carrying operations. The results of this contract will help to form the basis for planning future R&D efforts.

Mr. Gene A. Birocco, Military Operations Technology Division, served as project engineer for this effort.

Task 1F162203AA3303
Contract DAAJ02-72-C-0063
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SUMMARY

A. PURPOSE AND SCOPE

The very significant and effective use of external cargo carriage by Army helicopters in support of ground troops – as recorded in the Vietnam conflict – has, in part, been compromised by the implied high failure rates of the external cargo-handling systems involved. However, the exact magnitude, characteristics, and causes of these failures have not to date been well understood. Without a clear understanding of these elements, a program of corrective action becomes almost impossible to initiate. Moreover, if the basic causes of these high failure rates remain unknown and unresolved, the external carriage potential of the next generation of heavy-lift helicopters could be seriously jeopardized as well. For this reason, the Army's Air Mobility Research and Development Laboratory (AMRDL), Eustis Directorate, requested proposals for a comprehensive failure analysis of these systems early in 1972. Arthur D. Little (ADL) Inc. was awarded the contract shortly thereafter and immediately formed a study team to analyze the inherent problem with the objective of (1) identifying, developing, and subsequently recommending cost-effective, corrective actions to diminish the current failure rate and, concomitantly, (2) increasing the productivity of current external cargo-handling systems. A secondary objective was to identify potential problem areas in future heavy-lift systems by extrapolating data compiled in the study.

The scope of work in ADL's approach to realizing these objectives embraced nine specific tasks, including

(1) an overview of external cargo-handling helicopter operations;

(2) a search of pertinent literature;

(3) a sampling of the documented failure data base;

(4) formulation of a detailed data retrieval plan;

(5) actual retrieval of pertinent data;

(6) data compilation;

(7) data analysis and presentation;

(8) development of candidate areas for corrective action; and

(9) recommendation of corrective actions.

(Each of the tasks is explained in some detail in Chapter II-B.)

Our initial efforts to compile the pertinent data needed to perform our planned analysis indicated that the available data were not comprehensive enough to fully support the original objectives of the program. Specifically, we found that the data would not support a completely quantitative analysis of such contributions to the cause of failures as human error versus unjustifiable mechanical failures, pilot-induced oscillations, unstable loads, and human error versus supply/logistics deficiencies. Furthermore, we found that the data were not definitive enough to allow a completely descriptive and quantitative analysis of design or qualification testing and specification, maintenance, training, and improper work stations. Thus, with the concurrence of AMRDL, we slanted our study toward a more qualitative analysis of these particular areas of concern.

B. DATA SEARCH AND COMPILATION

1. Definition and Function

As the first step in our analysis, we defined a helicopter's external cargo-handling system to be that machinery, materials, and human controls which act in concert to move cargo external to the aircraft. This definition embraces both people – in the form of the pilot, the air crew, and the ground crew – and equipment and materials – in the form of the external cargo-handling rigging gear, such as slings and pendants; the cargo itself, that is, CONEX containers, eyebolts on equipment, and the like; and certain cargo-related parts of the helicopter, for example, the hook and controls. These parts function as a system, of course, only when they are actually involved in handling external cargo.

From this definition the failure of an external cargo system can be defined as any occurrence which, because of adverse interreactions of the component parts of the system, effects significant damage to the cargo or the helicopter or injury to the personnel involved. This definition excludes certain losses, such as those caused by engine failure and ground fire damaging the aircraft.

In assessing system failures, the manner in which the system functions is basic. In all the failures analyzed in this report, loads were picked up or delivered from the helicopter's hover position – the point at which the involvement of the air crew and the helicopter actually begins. At the hover, the pilots and air crewmen work together to position the helicopter over the load. Once the external connections are effected, the air crewman notifies the pilot who commences lift-off. Then, when sufficient altitude is achieved, the pilot assumes a level flight pattern at a greatly increased speed. Breaking the level flight, assuming the hover position, and disconnecting the load completes the operational cycle. Simply stated, this constitutes the operation of an external cargo-handling system.

2. Operational Parameters

The basic operational parameter of a helicopter is measured in terms of sorties – the flights, landings, or hovers of a single helicopter. In a combat profile, the average cargo helicopter operating from the logistical base would probably perform most of its sorties out to the batallion and brigade bases.* Thus, most sorties are relatively short, perhaps less than 30 miles, requiring an estimated 20 minutes each. It is within this type of operational parameter that we have analyzed the various types of external cargo-handling system failures.

3. Failure Assessment Criteria

Because early in the program we found the data on specific failures far from comprehensive – typically descriptions of failures gave no key to their causes and interrelationships – we established rigid rules for assessing the failures. These rules were primed to highlight the root causes of the failures as opposed to any secondary contributing factors (see Section III-D). In addition, we determined where specific failures occurred in the flight (sortie) progression – pickup, delivery, or cruise – and the density of the load being carried when the failure occurred.

4. Data Sources and Retrieval

Initially we proposed an approach to identifying gross parameters of the whole expanse of external cargo-carrying with the objective of then focussing on the specifics of the problem, using this knowledge as a background. Then, with the overview data complemented by information garnered from an extensive literature search, we took a close look at the documented failure data on the system. Finding these data to be inadequate, we formulated a data retrieval plan and technique which relied heavily on consensus opinion data and failure reports compiled through personal interview. The interview formats are presented in Section III-F.

C. DATA PRESENTATION AND ANALYSIS

1. Load Categories and Rigging Materials

We concentrated our analysis on helicopters active in Vietnam in the 1968-1969 period, viz., the Marine CH-46, Army CH-47, Marine CH-53, and Army CH-54 helicopters, focussing our attention on six major categories of external loads carried and the distribution of the categories among loads that were typically carried by the various helicopters. The six categories included:

*See Figure 16 .

aircraft recoveries; single, unsupported loads; containerized loads; palletized loads; loads carried in nets; and chained/strapped-together loads. In addition we looked at the specific materials employed in rigging the external loads, viz., slings, straps, doughnuts, clevises, and other mechanical devices.

After conducting an exhaustive analysis of all failure data compiled by individual helicopter types, we prepared an overall summary of some 371 Army and Navy/Marine external cargo-handling failures involving the four helicopters previously cited. The analysis showed that, under the aircraft subsystem grouping (16.2%), the hook load release and controls accounted for an average of 12.8% of the failures, followed by pendants and winches, respectively; under riggings (36.1%), slings accounted for 25.2% of the failures, followed by straps, doughnuts, clevises, and other mechanical devices, respectively; under load containers and attachments (9.2%), nets accounted for 6.9% of the failures; and under human errors (39.4%), pilots accounted for 24% of the failures, followed by pilot/air crew, air crew, and ground crew in that order (see Table X).

We next compared our documented data with our consensus data for two of the aircraft – the CH-47 and the CH-54 – omitting human error entirely. The results are shown in Table I. It was interesting to note that the pilots and air crewmen appeared to be substantially more optimistic about the reliability of the helicopter subsystem than the evidence seemed to warrant, albeit they were unduly pessimistic about certain subsystem components external to the helicopter.

2. Analysis

Our analysis was based on actual failures as measured against various load densities and various segments of a flight's progression. For instance, Figure 1 gives a graphic presentation of the causes of overall failure occurrences experienced by three* helicopter types – the CH-47, CH-53, and CH-54 – as a function of three classes of loads – low-, medium-, and high-density. Figure 2, on the other hand, presents cause of failure occurrences as a function of flight progression, viz., pickup, in-flight, and delivery. Several interesting observations were made:

- Slings and pilot errors represented the two largest – about equal in magnitude – causes of failures;
- Hook failures were substantial;

*There was insufficient data on a fourth, the CH-46.

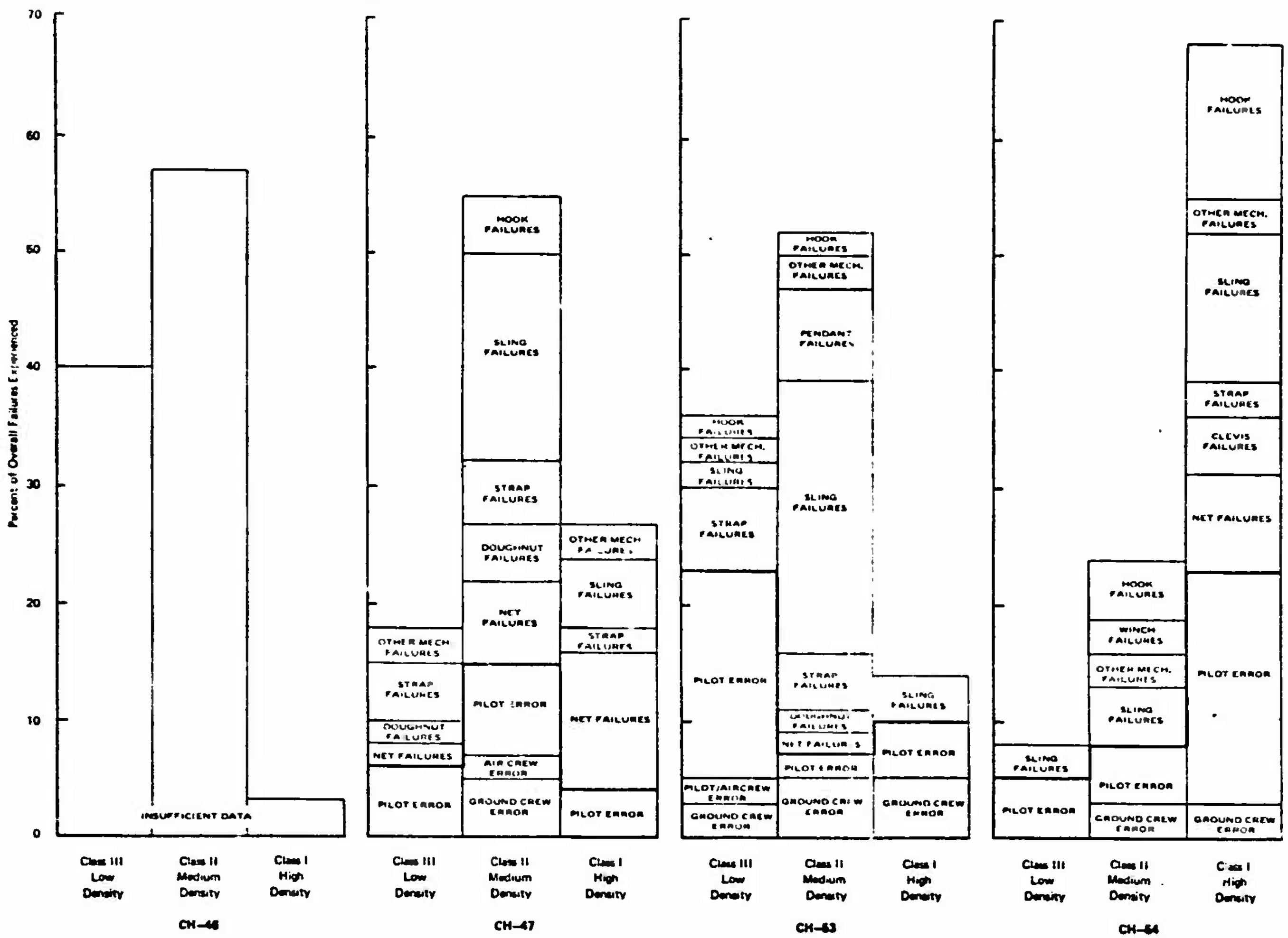
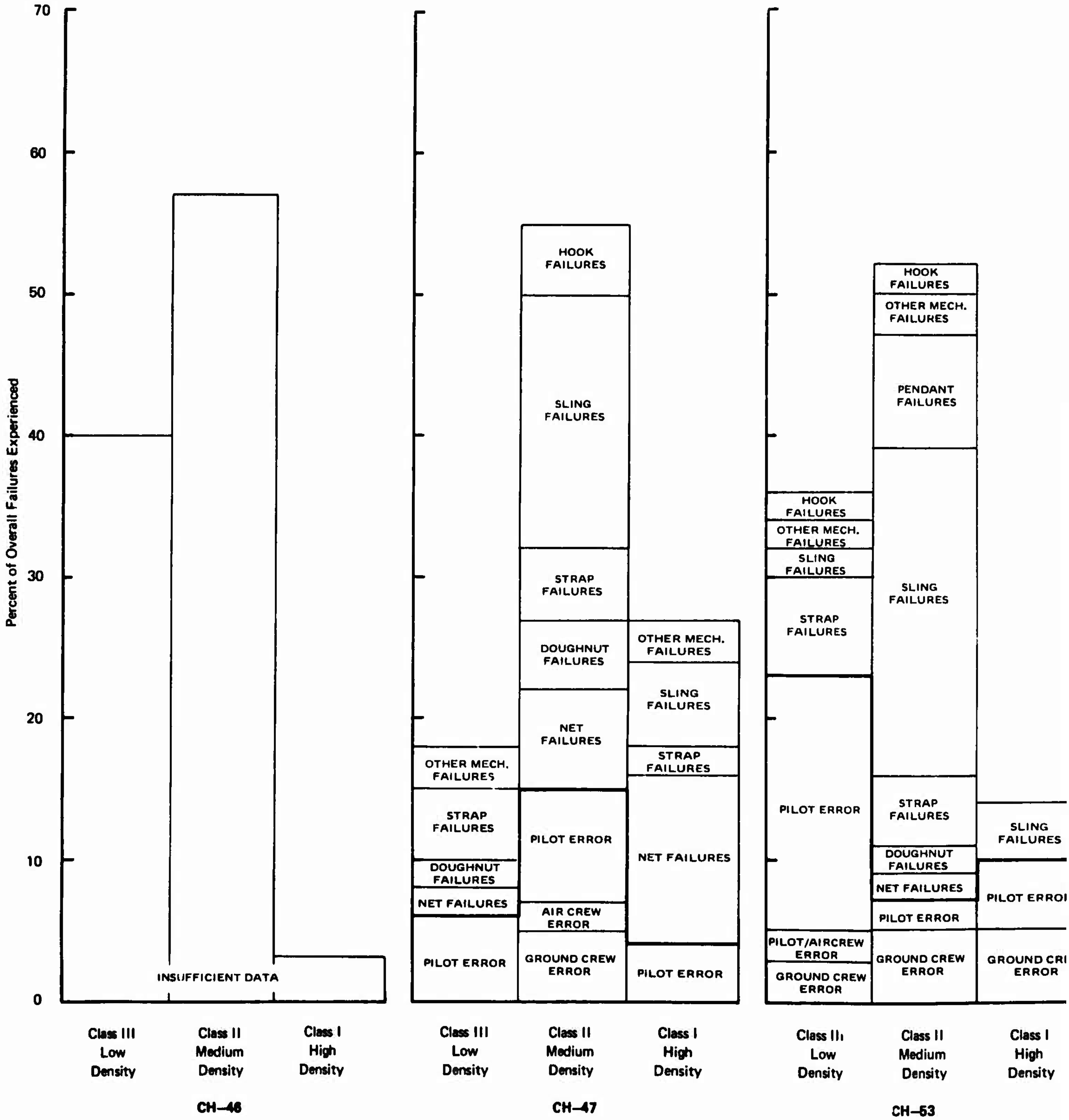


FIGURE 1 - DENSITY AND CAUSE-OF-FAILURE DISTRIBUTIONS TYPICAL OF EXTERNAL LOADS CARRIED IN HELICOPTERS IN VIETNAM.



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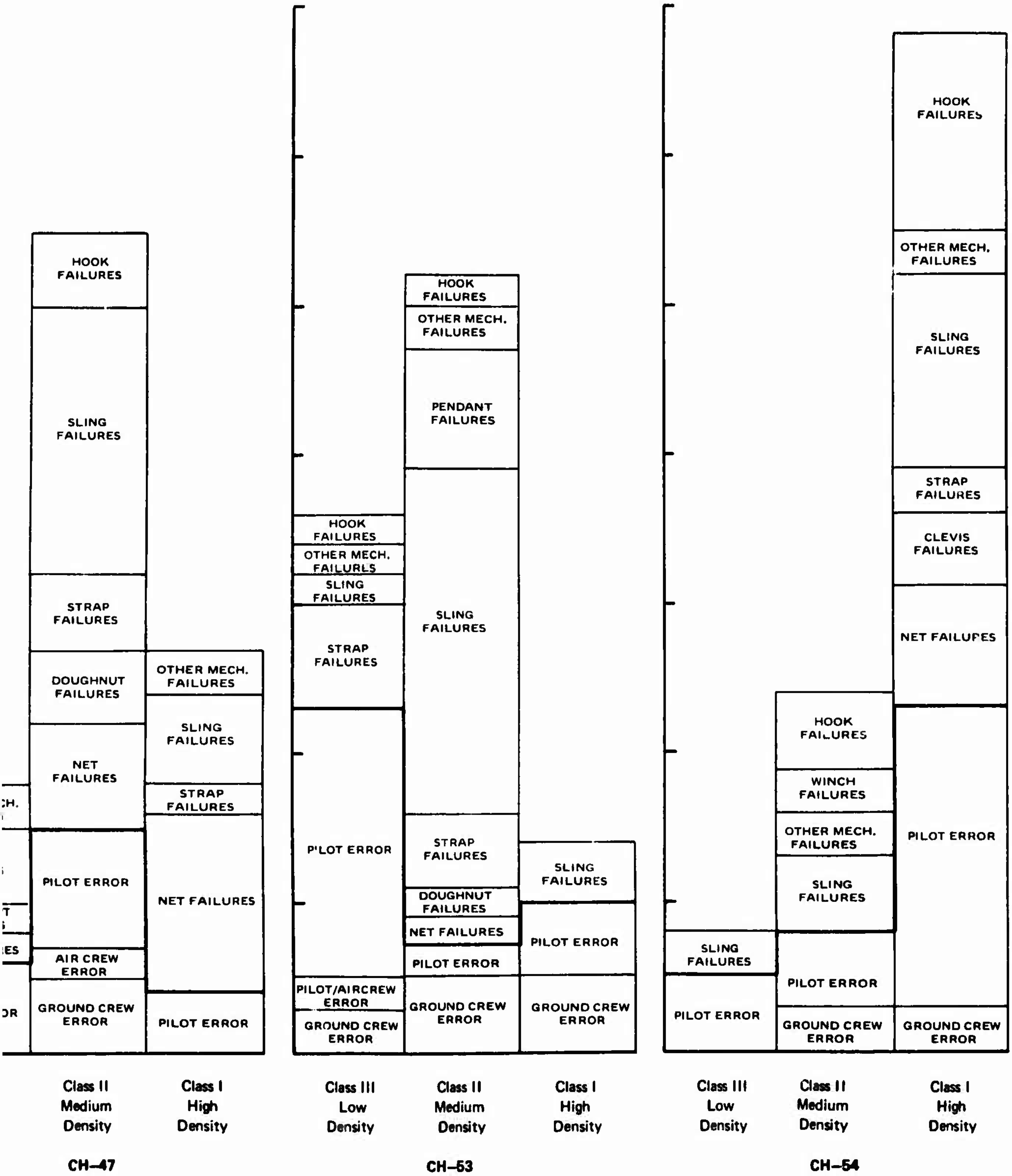

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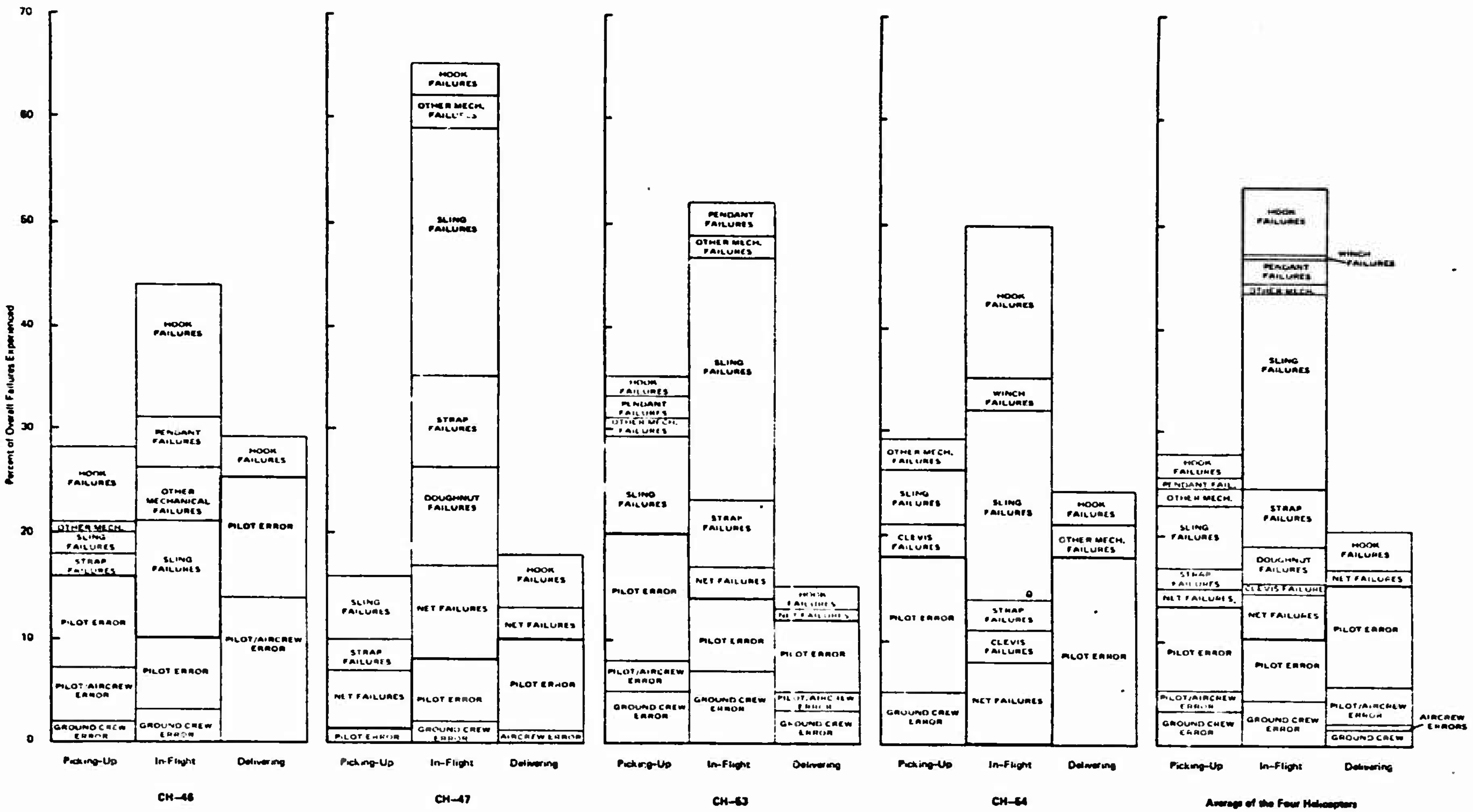

FIGURE 2. CAUSE OF OVERALL FAILURES EXPERIENCED IN TYPICAL RUN UNIT VERSUS TASK PROGRESSIONS.

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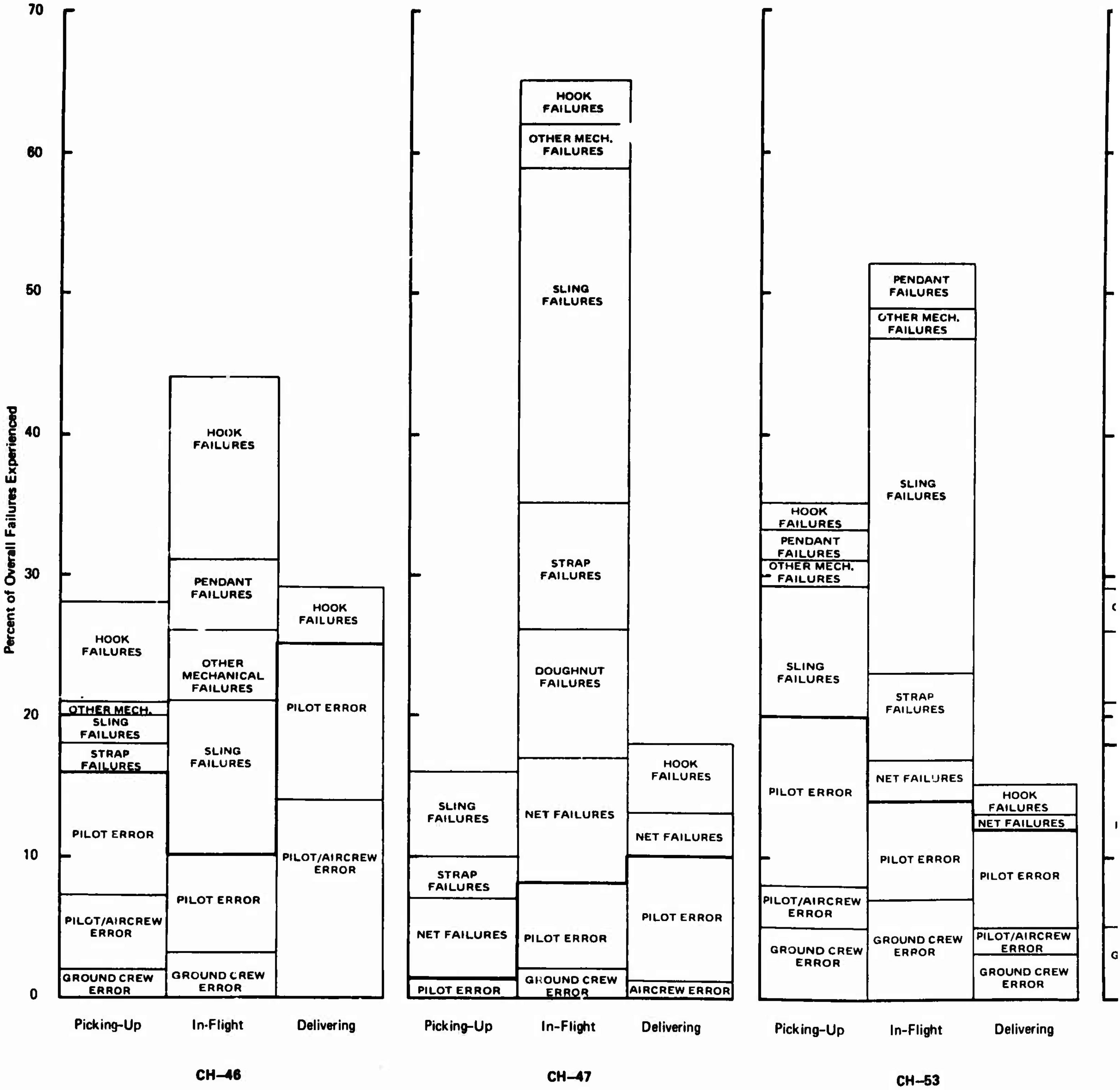

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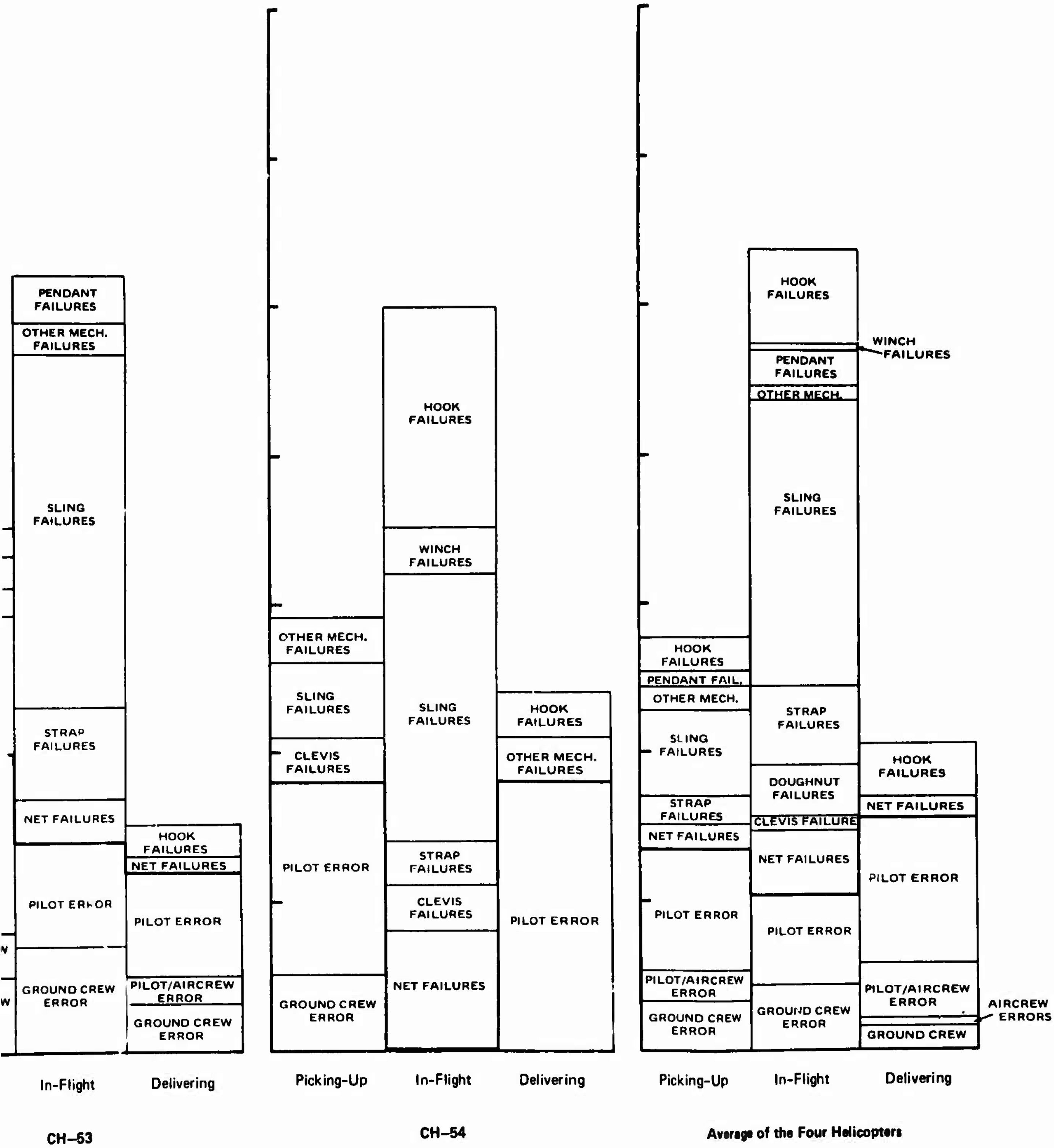
PENDANT FAILURES
OTHER MECH. FAILURES
SLING FAILURES
STRAP FAILURES
NET FAILURES
PILOT ERROR
GROUND CREW ERROR
HOOK FAILURES
NET FAILURES
PILOT ERROR
PILOT/AIRCREW ERROR
GROUND CREW ERROR
In-Flight
Delivering
CH-53
OTHER MECH. FAILURES
SLING FAILURES
CLEVIS FAILURES
PILOT ERROR
GROUND CREW ERROR
HOOK FAILURES
WINCH FAILURES
SLING FAILURES
STRAP FAILURES
CLEVIS FAILURES
NET FAILURES
HOOK FAILURES
OTHER MECH. FAILURES
PILOT ERROR
Picking-Up
In-Flight
Delivering
CH-54
HOOK FAILURES
PENDANT FAIL.
OTHER MECH.
SLING FAILURES
STRAP FAILURES
NET FAILURES
PILOT ERROR
PILOT/AIRCREW ERROR
GROUND CREW ERROR
HOOK FAILURES
WINCH FAILURES
PENDANT FAILURES
OTHER MECH.
SLING FAILURES
STRAP FAILURES
DOUGHNUT FAILURES
CLEVIS FAILURE
NET FAILURES
PILOT ERROR
GROUND CREW ERROR
HOOK FAILURES
NET FAILURES
PILOT ERROR
PILOT/AIRCREW ERROR
AIRCREW ERRORS
GROUND CREW
Picking-Up
In-Flight
Delivering
Average of the Four Helicopters

TABLE I

COMPARISON OF DOCUMENTED TO CONSENSUS DISTRIBUTIONS OF MECHANICAL FAILURES

	Percentage of Overall Failures Experienced			
	CH-47		CH-54	
	Documented	Consensus	Documented	Consensus
Aircraft Subsystem				
• Hook load releases & controls	11.7	3.4	27.7	4.0
• Winches	0	0	4.6	2.6
• Pendants	0	1.1	NA	–
	11.7	4.5	32.3	6.6
Rigging				
• Slings	36.4	33.2	35.4	58.3
• Straps	15.6	1.9	4.6	4.2
• Doughnuts	10.4	10.3	NA	–
• Clevises	1.3	0.8	7.7	4.1
• Other Mech. (drogue chutes)	1.3	1.9	0	1.7
	65.0	48.1	47.7	68.3
Load Containers & Attachments				
• Nets	22.1	42.3	12.3	15.8
• Other Mechanical Items	1.3	3.8	7.7	9.1
	23.4	46.1	20.0	24.9
Total	100.1	98.7	100.0	99.8

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- Four other significant causes of failure – all about equal in magnitude – were straps, nets, pilot/air crew (guidance/collision) errors, and ground crew (rigging) errors.

In addition to our failure occurrence data, we also developed failure rate data which related the incidence of failure to a common operational measurement (sorties) for each helicopter type. Failures per sortie, of course, could readily be converted into failures per operational hour, since this relationship was known for each helicopter. Unfortunately, only data on the CH-47 proved to be sufficient for developing the failure rate relationships. Fortuitously enough, however, the CH-47 carried 81% of all cargo carried in Vietnam during the period analyzed (1968 and 1969).

Figure 3 presents the failure rate of the CH-47 by load category, and shows the high failure rates of strapped-together loads and disabled aircraft recoveries.

Figure 4 presents failure rate distribution relationships by flight progression and load density for the CH-47 and, in particular, shows a very high rate of failure in the high-density load category, almost 13 failures per 1000 sorties. In the sortie progression area, most failures occurred in the cruise flight mode.

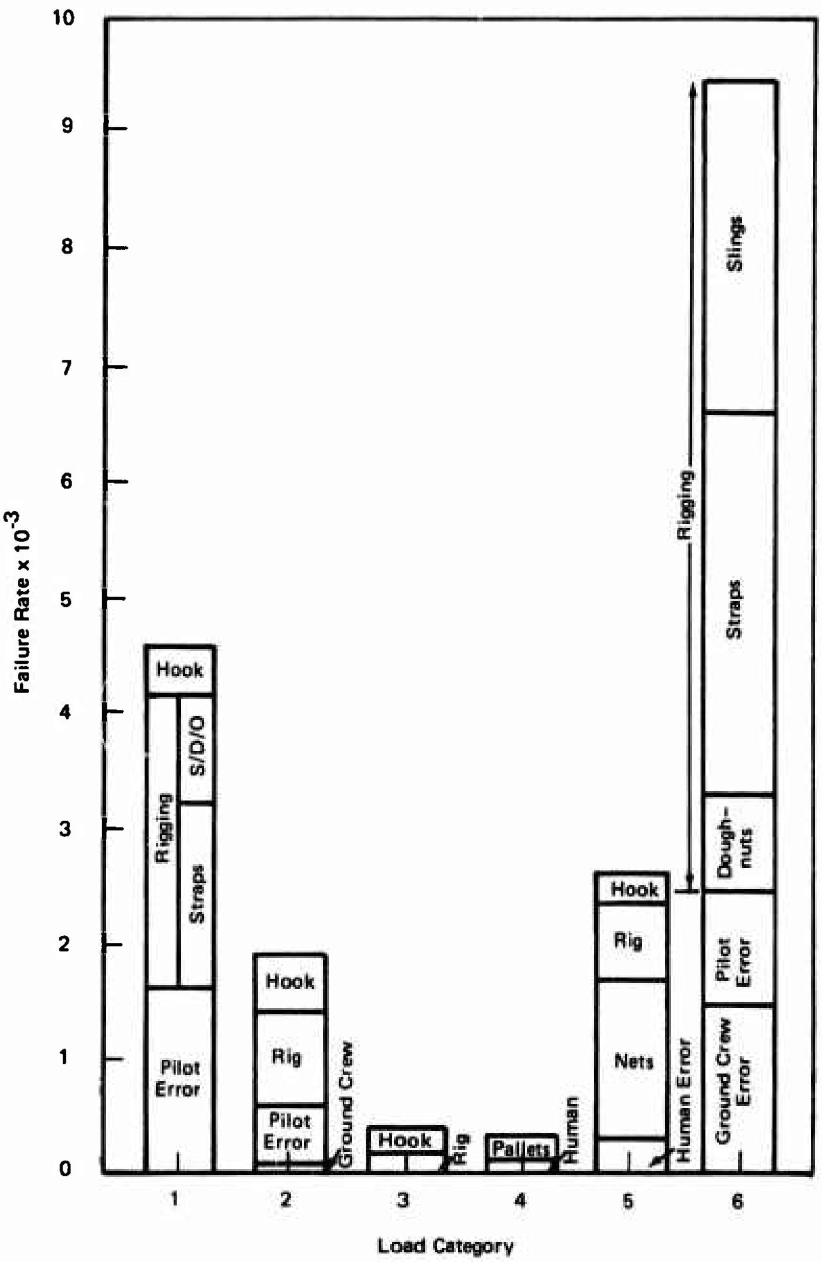
Detailed failure rate breakdowns by sortie progression for the CH-47 are presented in Figure 5. As previously indicated, most failures occurred in the cruise flight mode. Various rigging equipment accounted for most failures, and slings were the most frequent cause of failure. Pilot error was also in evidence in the cruise flight and delivery mode failures.

Figure 6 presents failure rate breakdowns by load density for the CH-47. Net failures were dramatically predominant in failures involving high-density loads. Rigging failures were predominant in failures involving low- and medium-density loads.

Our most important general observation is that mechanical failures occur predominantly in flight and increase dramatically when high-density loads are carried.

We were also able to make certain observations concerning the cause of failures in specific helicopters. For instance:

- The CH-53 and CH-54 helicopters have basically the same hook. Therefore, we assumed that the significantly large number of hook failures in the CH-54 must be caused by the swivel commutator and electrical equipment unique to it.



Load Categories:

1. Disabled A/C
2. Single Unsupported
3. Containers
4. Pallets
5. Nets
6. Strapped

FIGURE 3. FAILURE RATE BY LOAD CATEGORY.

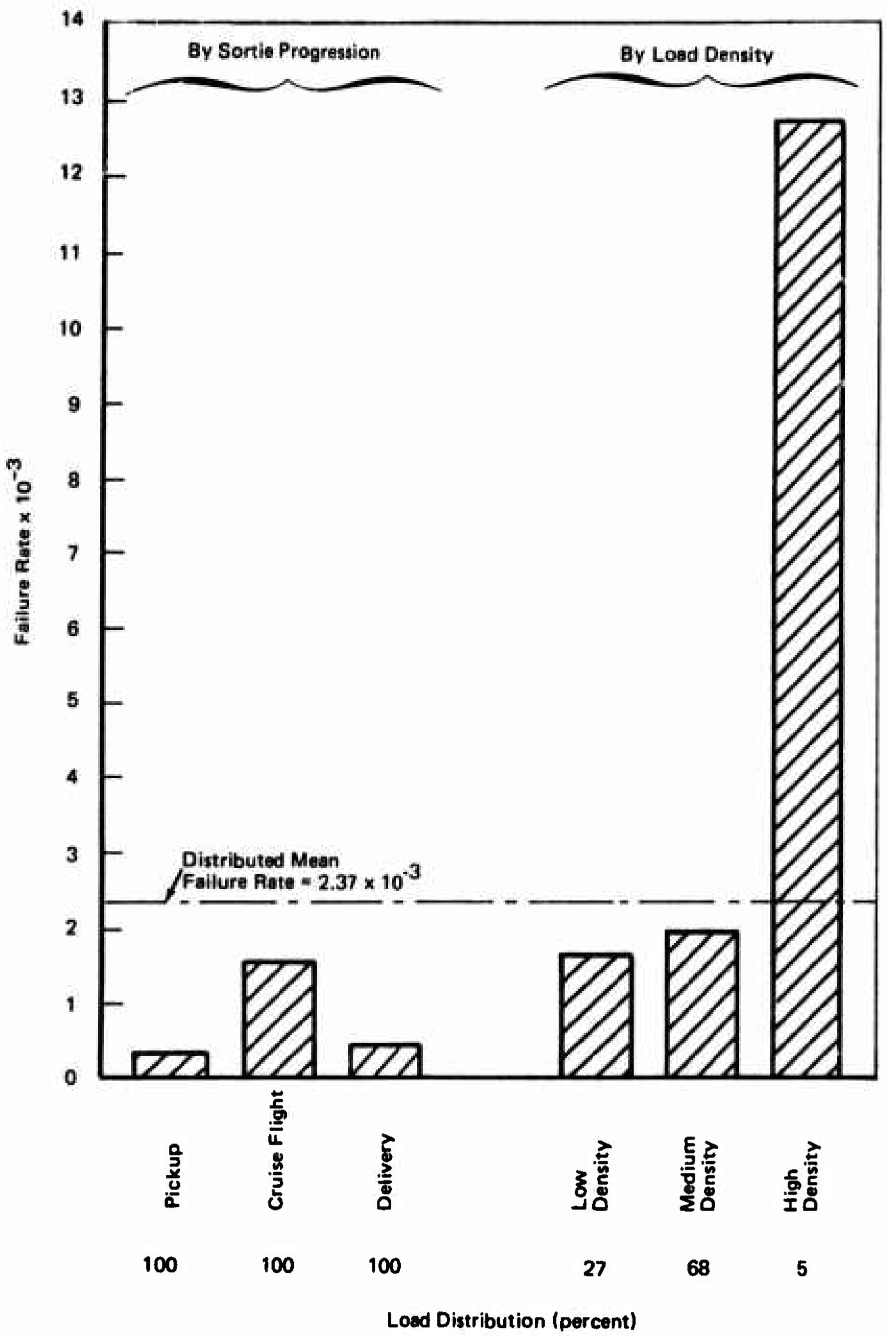


FIGURE 4. FAILURE RATE DISTRIBUTION RELATIONSHIPS (CH–47).

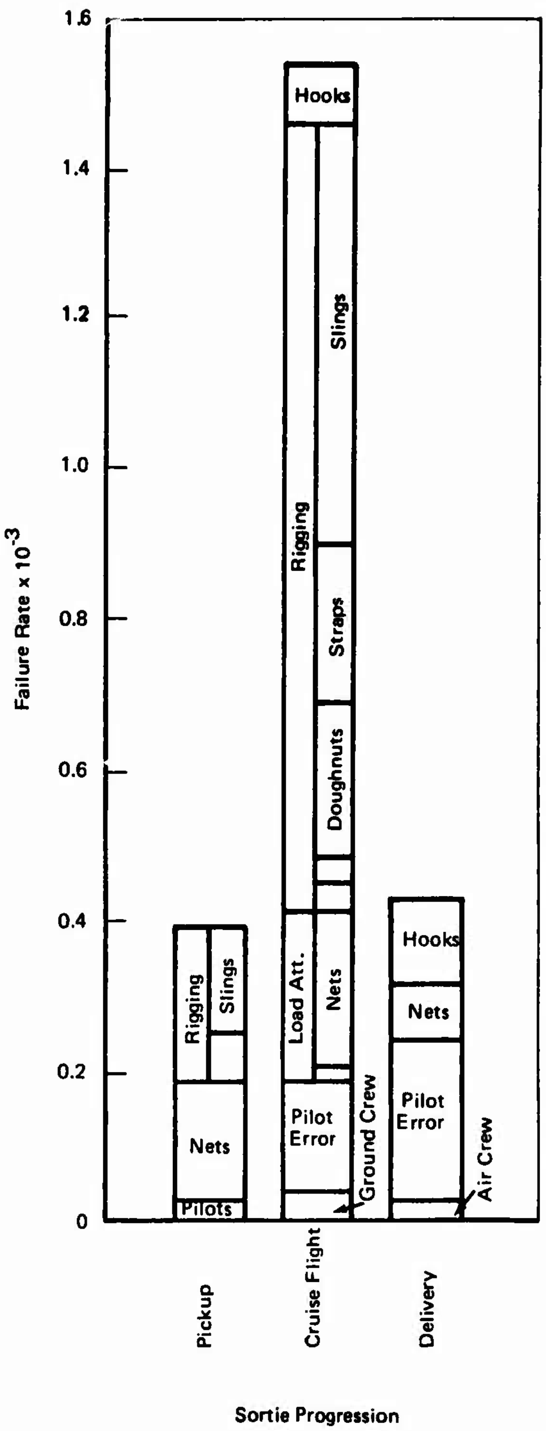


FIGURE 5. FAILURE RATE BREAKDOWNS BY SORTIE PROGRESSION (CH-47).

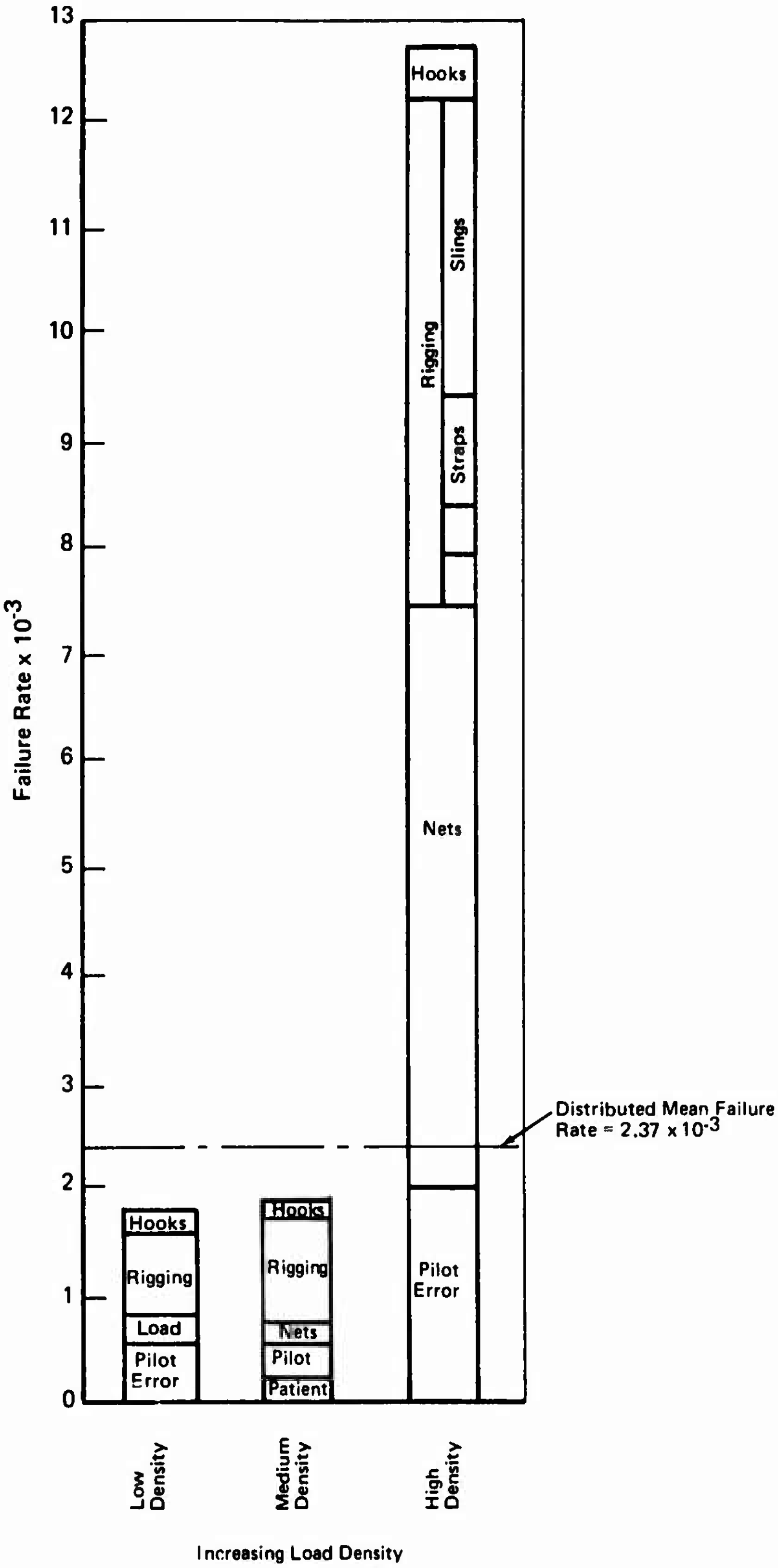


FIGURE 6. FAILURE RATE BREAKDOWNS BY LOAD DENSITY (CH-47).

- The high number of sling failures in the CH-53 may be related to the high number of ground crew errors.

- Net failures are almost unique to the Army, but only with its CH-47.

Analysis of our failure rate data led to some interesting conclusions:

- Strapped, or chained-together, loads have, by far, the highest failure rate, being more than double that of the second most failure-prone load – disabled aircraft recoveries.

- Next in line were net loads and single, unsupported loads, respectively, which showed failure rates approximately half that for disabled aircraft recoveries.

- Container and palletized loads have very low failure rates – a small fraction of any other load category.

Other pertinent facts revealed in our analysis:

- There was a disproportionate amount of pilot error involved in aircraft recovery loads.

- The high failure rate in the strapped-together load category seemed to be a dual problem of rigging and human error.

- The relatively high failure rate of net loads can be attributed principally to failure of the nets themselves.

- Mechanical components (principally rigging) showed a high failure rate in the cruise mode. Our failure occurrence data showed pilot error to be minimal during pickup, increasing during cruise flight, and peaking substantially during delivery.

- Of paramount interest is the apparent extremely high failure rate associated with high-density loads, their rate appearing to be 6 to 8 times that of low- and medium-density loads. Surprisingly enough, net failures were the predominant causes of these failures, accounting for 44% of combined causes of failures with these loads. Net failure, in this case, even exceeded combined rigging failure at 37% of the total.

D. RECOMMENDED CORRECTIVE ACTIONS

Our analysis resulted in the following ranking of the most significant causes of failure of external cargo-carrying systems:

- Sling failures,
- Pilot errors,
- Net failures,
- Strap failures, and
- Hook failures.

Much R&D effort is currently being expended on the development of more reliable rigging materials, including slings, straps, and pendants. Therefore, improvement in this area can well be expected in a reasonable time frame, and we do not consider rigging materials as a sensible candidate for corrective action under this contract. However, since our analysis showed that about 88% of the total replacement cost of all cargo dropped could be attributed to dropped aircraft, this appeared to be an area of prime consideration for corrective action.

We suggested four main areas for corrective action based on our analysis. They were:

- Aircraft recovery failures,
- Pilot errors,
- Net failures, and
- Hook failures.

E. DEVELOPMENT OF SPECIFIC CORRECTIVE ACTIONS

Following our analytical work, we continued our work in two areas:

- Development of a conceptual design for a collapsible cargo net-pallet combination; and

- Development of the requirements for a comprehensive research program to investigate cargo hook design principles.

These developments are covered in Chapter VII.

I. INTRODUCTION

A. HISTORY OF THE MILITARY HELICOPTER

The basic concepts and principles of both fixed-wing and rotary-wing aircraft were probably identified and modeled concurrently in the 1870's. The helicopter concept, in particular, stimulated the imaginations of inventors and theorists from that period onward. A vertical takeoff and landing aircraft would have the capability of relatively high speed and the ability to pass over obstacles encountered by surface vehicles. But, most important, it would also have the capability of landing in an area not much larger than its own dimensions. However, the flight dynamics, control functions, and power-to-weight ratio constraints of helicopter design proved to be much more difficult than for fixed-wing aircraft. For these reasons it was not until aeronautical engineers had developed considerable skills in engine, control, and power transmission design and strength-to-weight optimization that the helicopter was successfully developed.

Noted inventor Thomas Edison succeeded in blowing up half of his laboratory in the 1880's attempting to develop that lightweight engine necessary to make helicopters successful. Unfortunately he thought an engine propelled by gunpowder might be the answer.

Helicopters that would fly marginally in ground effect date from about 1907 and ones similar to modern configurations from about 1912. Igor Sikorsky, then a student engineer in Russia, built an unsuccessful helicopter in 1910. He later emigrated to the United States and concentrated on fixed-wing aircraft, only to return to the study of helicopters some 30 years later.

Work began on the first Army Air Corps helicopter in 1921. In an initial effort, Dr. George de Bothezot, an émigré Russian professor, designed and constructed a four-rotor machine powered by a 180-hp LeRhone engine. This helicopter made more than 100 flights, rising to heights ranging from 15 to 20 feet. Thomas Edison, having abandoned his gunpowder engine, hailed de Bothezot's aircraft as the first successful helicopter.

The Army eventually abandoned de Bothezot's design because it was too complex mechanically. However, it had successfully lifted 4,400 pounds, which perhaps foretold, even at that time, the future potential for cargo helicopters. In truth, none of these early helicopters was capable of the combined requirements of lifting out of ground effect, adequate flight control, and a reasonable forward speed.

However, by the 1930's those engaged in rotating wing research – and they were many – realized that the age of the helicopter was close at hand. Much of

the theory was known; even the actual components existed in one form or another due in part to the intensive work that had gone into the perfection of autogyros in the interim period. This theory became a reality in the late 1930's when the Germans, in particular, developed several successful helicopters.

In the United States, Sikorsky reemerged in helicopter technology in 1939/40 when his R-48 helicopter was first flown. While it was several years behind the German helicopters in development, it went on to become the first helicopter produced in the United States in other than experimental quantities. After preliminary tests were conducted, a contract for 100 such aircraft was awarded by the Army in 1943. Some of these helicopters, in fact, saw action during World War II.

The Army's need for helicopters subsequently was firmly established in 1947, and the outbreak of the Korean war in 1950 created opportunity for the helicopter to prove what was to become its very great utility in the support of ground warfare. As quickly as the helicopters could be manufactured and personnel trained, they were sent to units deployed in Korea. The initial helicopter shipments consisted of the small H-13 and H-23 models – two- and three-place craft, respectively. They were immediately put into service evacuating wounded and providing observation and transportation for division commanders.

As soon as they were available in 1952, larger cargo-type helicopters, principally the H-19, were also sent to Korea. They provided, for the first time, a means of moving troops and equipment rapidly, and were instrumental in saving thousands of lives by quickly evacuating the wounded from front-line positions to rear-area hospitals. The 30th Medical Group alone, with 18 two-place helicopters, evacuated more than 20,000 casualties. There were only two cargo helicopter companies in Korea, the 6th and 13th, which had 21 cargo helicopters each. However, these few helicopters proved their worth there – out of all proportion to their numbers – in evacuating wounded and supplying units in the front lines.

The Army emerged from the Korean war with the realization that Army aviation possessed the capability of revolutionizing the techniques of deploying ground forces. In 1953, the 506th Transportation Company was assigned to the Infantry School at Fort Benning, Georgia, to be used further in developing techniques and doctrine in the tactical employment of transport helicopters. A year or so later, the Army Aviation School at Fort Rucker, Ala., started conducting tests on helicopter armament, and the Artillery School at Fort Sill, Oklahoma, conducted tests on helicopter-borne artillery. While the reliability, particularly of these early helicopters, left much to be desired (typically 600 hours between airframe overhauls) and they proved to be relatively costly, their very great utility far outweighed these shortcomings.

During the period of the 1950's to early 1960's considerable helicopter experimentation was sponsored by the military. Their goal was lower costs and more reliable designs. This era saw the development of the McCullough YH-30 belt-driven helicopter, the American YH-26 pulse jet, and the Hiller UH-32 ram jet. Some dramatically different configurations were the Curtiss-Wright VZ-7AP "Aerial Jeep" and the Hiller XROE-1 "Rotorcycle." These designs, for various reasons, proved not to be fully suitable. In fact, helicopter configurations – with the possible exception of the tandem-rotor configuration – have never radically departed from the original Sikorsky configuration.

In early 1961, the United States Army committed the first helicopter companies to the Republic of Vietnam as a means of improving the mobility of units there. In 1963, the turbine-powered UH-1 helicopters were sent there, followed in 1966 by the CH-47's and later the CH-54's. The increased effectiveness of ground troops supported by helicopters was so dramatic there that plans for increases in helicopter organizations were immediately integrated into all levels of U. S. Army planning.

The 11th Air Assault Division (T) was established at Fort Benning, Georgia, in 1962 and developed the revolutionary idea of transporting troops and equipment into battle by helicopter for the next two years. Not since Hannibal's historic use of elephants, or Hitler's armored "blitzkrieg" in Europe, had such a concept so captured the imagination of the military or the general public.

As the conflict in South Vietnam began to escalate, it became more and more evident that sizeable U. S. helicopter units would have to be committed. During the 1962-1967 period, the United States Army deployed to South Vietnam the 1st Cavalry Division and the 1st, 4th, 9th and 25th Infantry Divisions, all of which had organic helicopters and personnel. By the peak period of the war in early 1970, the Army had approximately 2200 UH-1's, 300 CH-47's, and 30 CH-54's active in Vietnam. Their effectiveness had been proven, and the helicopter had become a permanent and respected piece of basic Army equipment.

B. HISTORY AND PROJECTIONS OF HELICOPTER CARGO-CARRYING

In helicopter combat-support cargo operations in Vietnam, it was found that the transport of cargo externally was much more expeditious than transporting it internally. It takes much less time (as little as 30 seconds) to connect to and lift off cargo to be carried externally as opposed to carrying loads internally that may take 10 or more minutes to be brought aboard and secured. Hence, helicopter productivity is substantially higher when external handling techniques are used. External carriage requires special preparation and rigging, but cargo must be comparably secured in the aircraft for internal carriage. The time and material requirements for both types of carriage are similar.

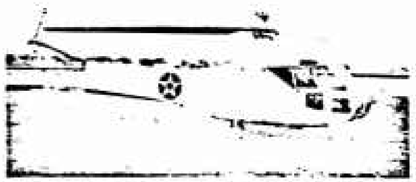
In internal carriage the pilot and air crew oversee the weight of the load admitted, load balance, and its securement in the aircraft. In external carriage the load is rigged independently by ground crews. Because of time and visibility constraints, this results largely in the pilot/air crew lifting relatively unknown load quantities in terms of weight, integrity of the rigging, and the probable aerodynamic characteristics of the load in flight. These factors, plus the inability of ground troops to maintain rigging/securement materials as well as air crews, introduces added risk for external carriage over internal carriage. These detriments constitute the price that has had to be paid for the greater utility of external carriage.

It is current Army policy to carry cargo externally wherever possible. In fact, external carriage in Vietnam rose to and stabilized at about 75% of all cargo carried by Army helicopters there. Areas of heavy tree coverage, or rough terrain where helicopters cannot land to load or unload, were common there, and external carriage was, in those situations, mandatory.

The first helicopter to carry external cargo in the Army was the Sikorsky H-19D "Chickasaw." This took place in Korea in 1953-54. The H-19, with a payload capacity of about 2000 pounds, was quickly replaced by the CH-21 and CH-34 models with payload capacities in the order of 5000 pounds. The CH-37 "Mojave," with a payload capacity of about 9,000 pounds, was introduced in 1957, and for about 10 years was the largest transport helicopter in the free world. Figure 7 is a montage showing early Army helicopters of importance.

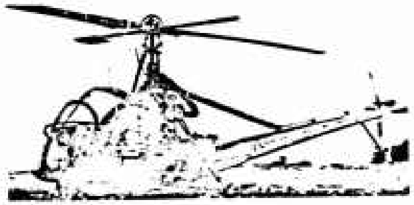
In 1961 the Russians introduced the jet-powered MIL-10 (Figure 8) with an external payload capacity of about 18,000 pounds. This development largely foretold future trends in cargo helicopters, since much Army field equipment, such as large trucks, bulldozers, 155-mm howitzers, and tracked personnel carriers, fell into this payload category.

The early piston engine-powered helicopters of the United States were made obsolete by turbine-powered helicopters starting in the early 1960's. The UH-ID "Iroquois," which went into operation in Vietnam in 1963, became highly successful utility helicopters but, because of their modest payload capacity and the fact that other larger cargo helicopters were readily available, they were little used for external cargo carrying. Early in 1966 the first CH-47 "Chinooks," with maximum external payload capacities of about 15,000 pounds, went into operation in Vietnam. Almost simultaneously, the CH-54 "Tarhes" went into operation with a maximum payload capacity of almost 20,000 pounds.

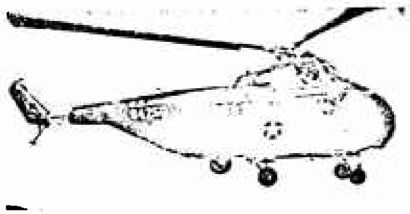


R4B "Hoverfly" 1943 to 1945		
	Length	48'2"
	Gross Wt.	2535#
	Engines/hp ea.	1/180
	Cruise Speed	64 mph
	Approx. Payload	500 lb

OH-13 "Sioux" 1948 to 1960		
	Length	27'4"
	Gross Wt.	2086#
	Engines/hp ea.	1/178
	Cruise Speed	85 mph
	Approx. Payload	500 lb



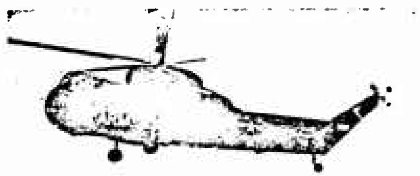
OH-23 "Raven" 1948 to 1959		
	Length	26'-6"
	Gross Wt.	2247#
	Engines/hp ea.	1/178
	Cruise Speed	76 mph
	Approx. Payload	750 lb



H-19 "Chickasaw" 1952 to 1954		
	Length	42'-2"
	Gross Wt.	7500#
	Engines/hp ea.	1/700
	Cruise Speed	93 mph
	Approx. Payload	3000 lb

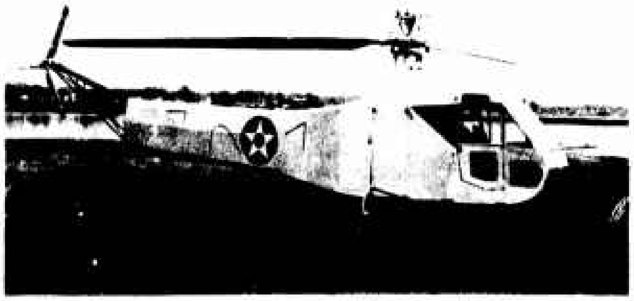
CH-21 "Shawnee" 1953 to 1968		
	Length	52'6"
	Gross Wt.	13,256#
	Engines/hp ea.	1/1425
	Cruise Speed	101 mph
	Approx. Payload	5500 lb

CH-34 "Choctaw" 1955 to 1961		
	Length	46'9"
	Gross Wt.	7630#
	Engines/hp ea.	1/1550
	Cruise Speed	117 mph
	Approx. Payload	5000 lb



CH-37 "Mojave" 1957 to 1965		
	Length	64'-10"
	Gross Wt.	30,188#
	Engines/hp ea.	2/2100
	Cruise Speed	115 mph
	Approx. Payload	9000 lb

FIGURE 7. EARLY ARMY HELICOPTERS OF IMPORTANCE.



R4B	Length	48'-2"
"Hoverfly"	Gross Wt.	2535#
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	Cruise Speed	64 mph
	Approx. Payload	500 lb

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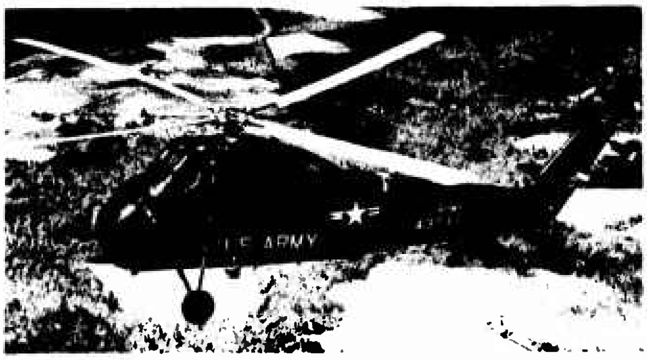

CH-34	Length	46'-9"
"Choctaw"	Gross Wt.	7630#
1955 to 1961	Engines/hp ea.	1/1550
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	Cruise Speed	76 mph
	Approx. Payload	750 lb

H-19	Length	42'-2"
"Chickasaw"	Gross Wt.	7500#
1952 to 1954	Engines/hp ea.	1/700
	Cruise Speed	93 mph
	Approx. Payload	3000 lb

CH-37	Length	64'-10"
"Mojave"	Gross Wt.	30,188#
1957 to 1965	Engines/hp ea.	2/2100
	Cruise Speed	115 mph
	Approx. Payload	9000 lb

Length:	107′ – 10″
Gross Weight:	83,775 lb
Engines/hp ea:	2/5,500
Cruise Speed:	112 mph
Approx. Payload:	17,635 lb

FIGURE 8. THE RUSSIAN MIL–10 FLYING CRANE HELICOPTER.

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In approximately the same time frame in which the Army CH-47's and CH-54's (Figure 9) were operating in Vietnam, the Navy/Marines were flying the CH-46's and CH-53's (Figure 10). They were comparable, but somewhat smaller, aircraft, and the total cargo tonnage they carried was only a fraction of that carried by the Army helicopters (about 10%). The Navy/Marine experience was predominantly with Marine troops, and it was thus largely similar to the Army's, i.e., in the support of ground troops. Increased emphasis on ship-to-ship and ship-to-shore helicopter transport (VERTREP) by the Navy may increase their proportion of total cargo helicopter usage in the future, however.

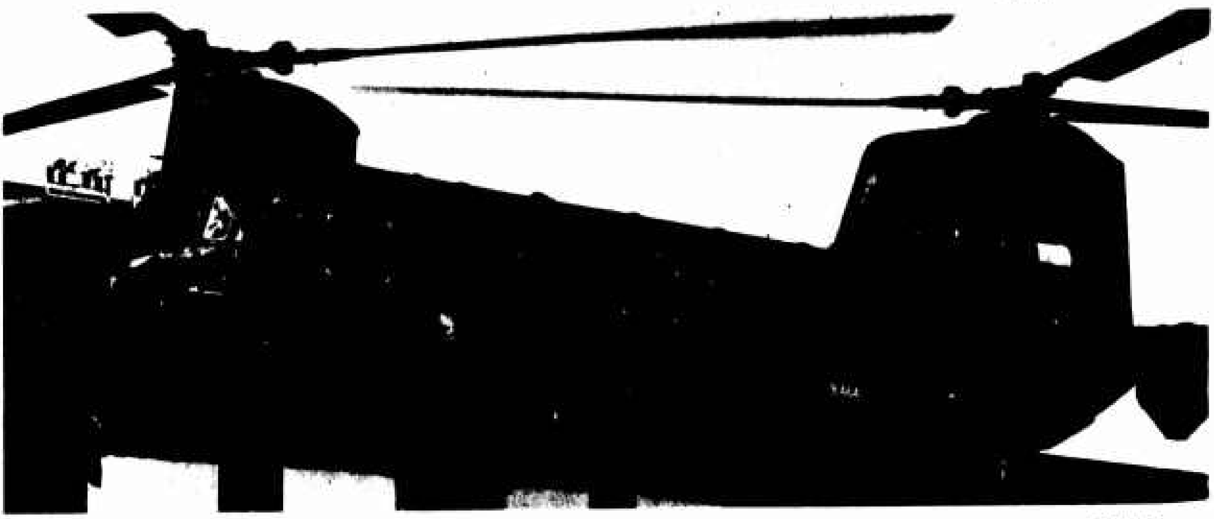
The need for a helicopter to lift heavy, outsized loads was first officially recognized by and documented by the Army in 1953. The need at that time was described as "a heavy-lift VTOL aircraft capable of lifting a 12-ton payload under sea level standard conditions." By 1968 this lift requirement was increased to 30 tons. Studies had indicated that this payload capability would permit the lifting of essential equipment and cargo to meet combat and support requirements in the future.

By 1970, the need for helicopters of increased payload capabilities was becoming increasingly apparent from both our own and Russian developments (see Figure 11). The Deputy Secretary of Defense, at that time, subsequently approved a joint Army/Navy program to exploit technology and develop the critical components for a 22.5-ton heavy-lift helicopter (HLH). Requests for proposals were distributed to the aircraft industry in November 1970, and subsequently the Secretary directed that a three-year advanced technology component (ATC) development contract be awarded to the Vertol Division of the Boeing Company. The HLH proposed by Boeing/Vertol is shown in Figure 12.

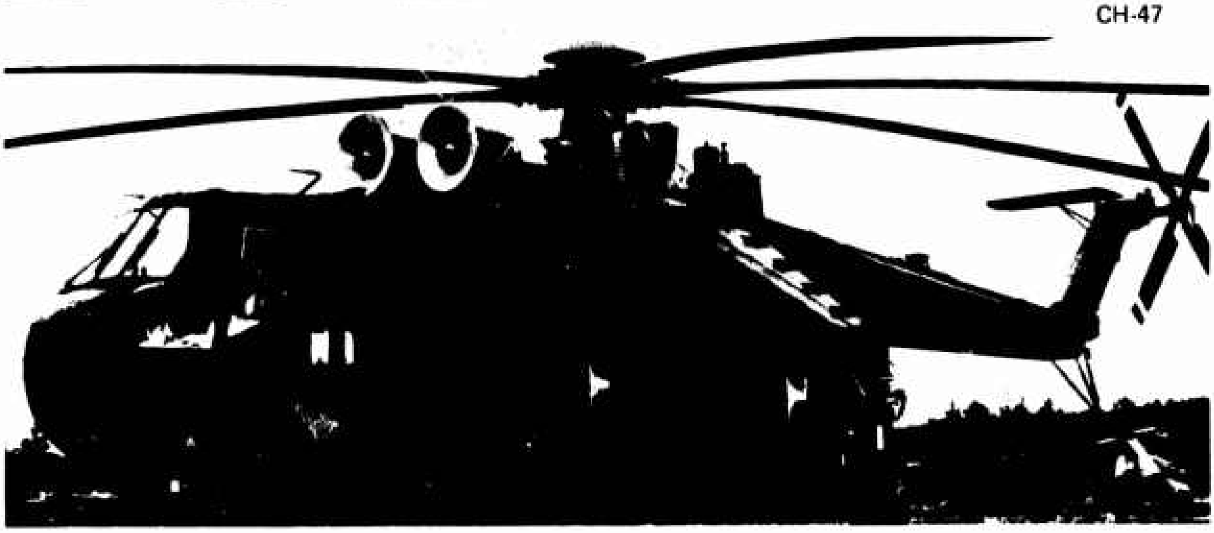
The first flights of production HLH units are scheduled for mid-1981. Of pivotal importance in the early stages of the HLH's development will be the advanced component technology task. A principal segment of this task will be to develop an advanced cargo-handling system that will allow the HLH to fully capitalize on its inherent capabilities. Principal among these is the capability of flying these heavy loads at cruise speed of around 150 knots. The subject study of this report, hopefully, will also make contributions toward realizing that goal.

Hard on the heels of military experience in external cargo carrying was the development of significant commercial experience. Commercial operators employing largely surplus military helicopters and ex-military helicopter pilots have developed a substantial industry, having become involved in such commercial ventures as erecting ski lifts, carrying air-conditioning units to the tops of tall buildings, and transporting power line towers to inaccessible areas – to cite just a few applications.

UH-1



CH-47



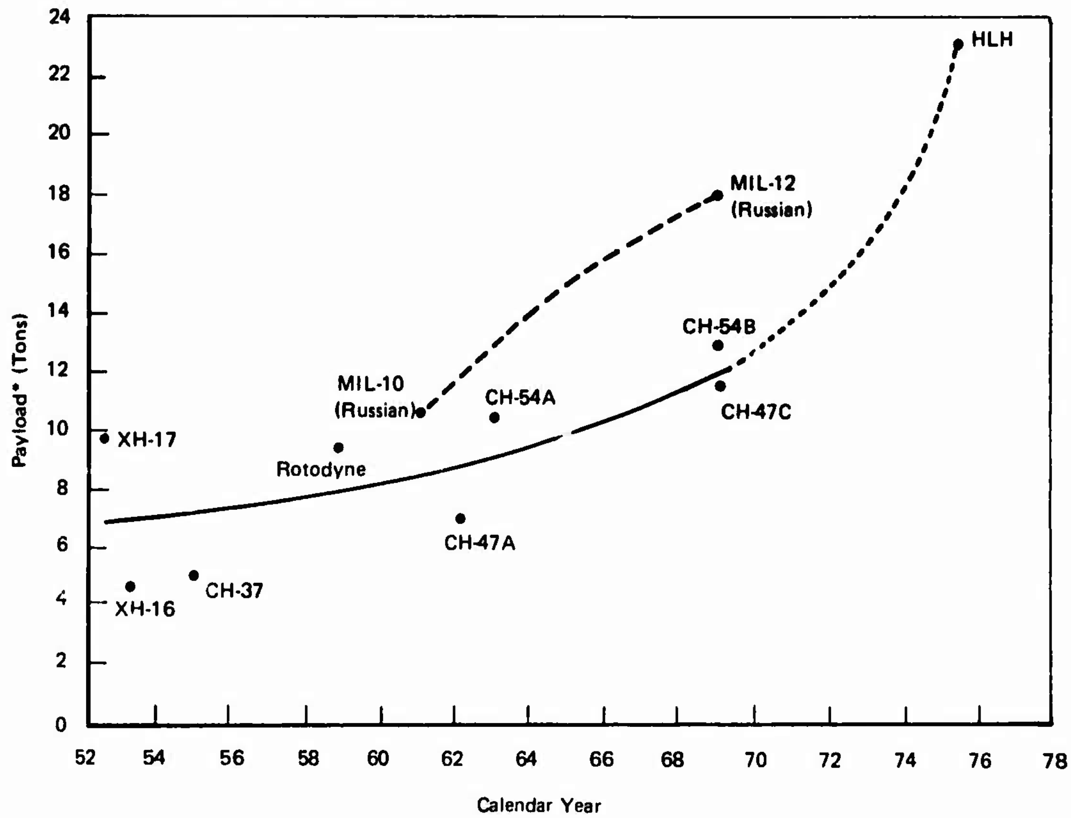
CH-54

FIGURE 9. CURRENT ARMY HELICOPTERS UTILIZED FOR CARRYING CARGO.

CH-46

CH-53

FIGURE 10. CURRENT NAVY/MARINE HELICOPTERS UTILIZED FOR CARRYING CARGO.

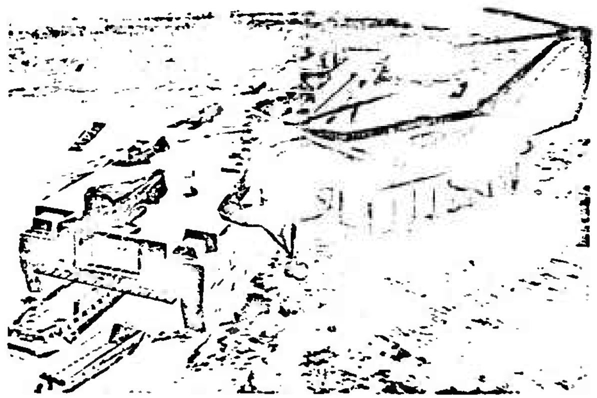


* Hover out of ground effect – sea level 95°F ambient

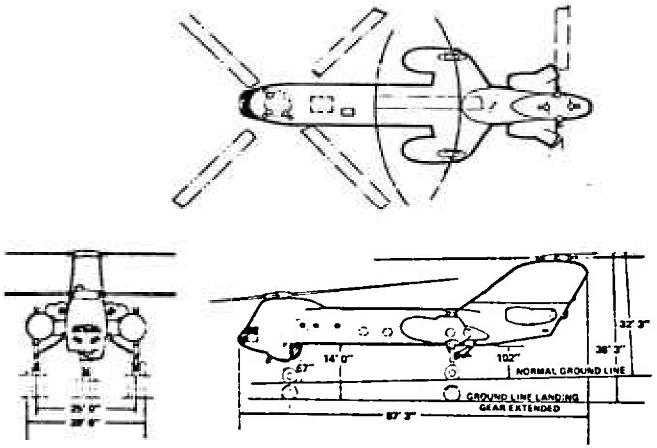
Source: U. S. Army Aviation Systems Command

FIGURE 11. HISTORICAL PROGRESSION OF HELICOPTER PAYLOAD CAPACITIES.

Logistics Support in the Forward Area



Navy Logistics Support



Weight (lb)	
Design Gross Weight	118,000
Design Payload	45,000
Design Mission Fuel	11,080
Fixed Useful Load	2,340
Empty Weight	59,580
Max Alternate Gross Weight, LF = 2.0	148,000

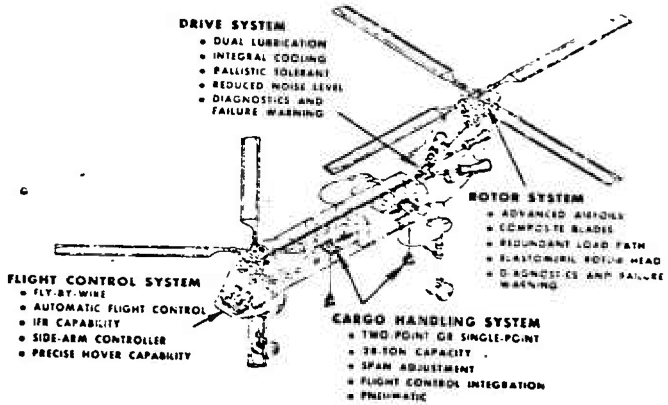


FIGURE 12. PROPOSED HLH HELICOPTER.

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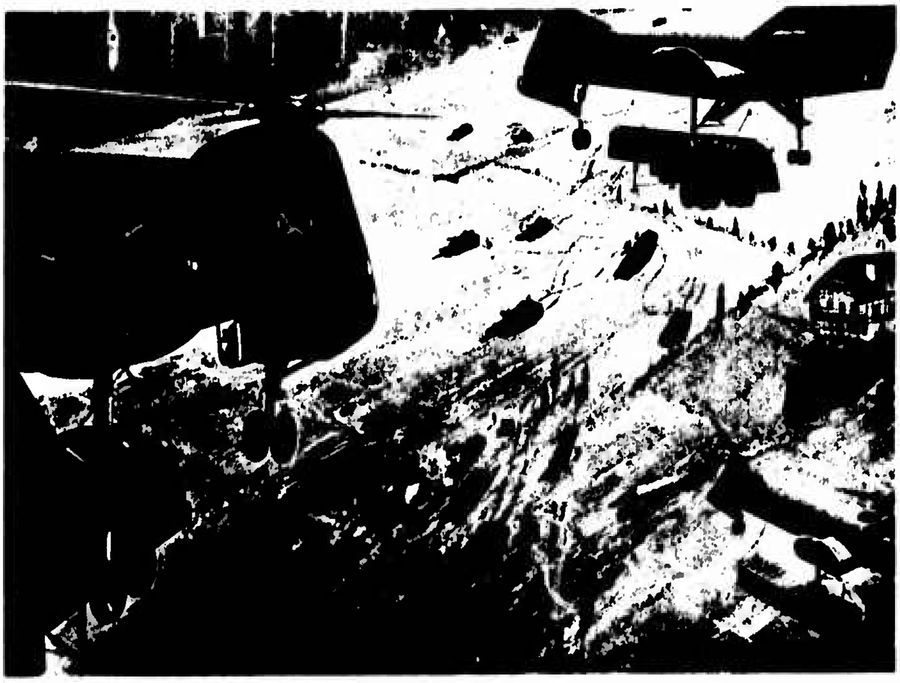
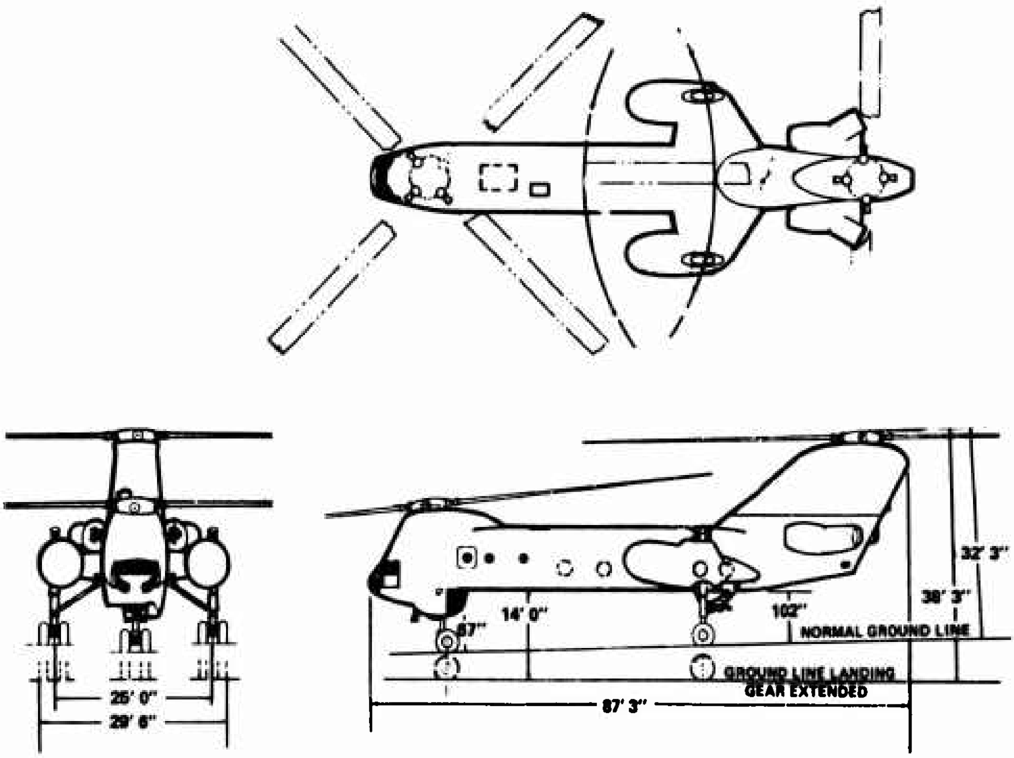


Logistics Support in the Forward Area



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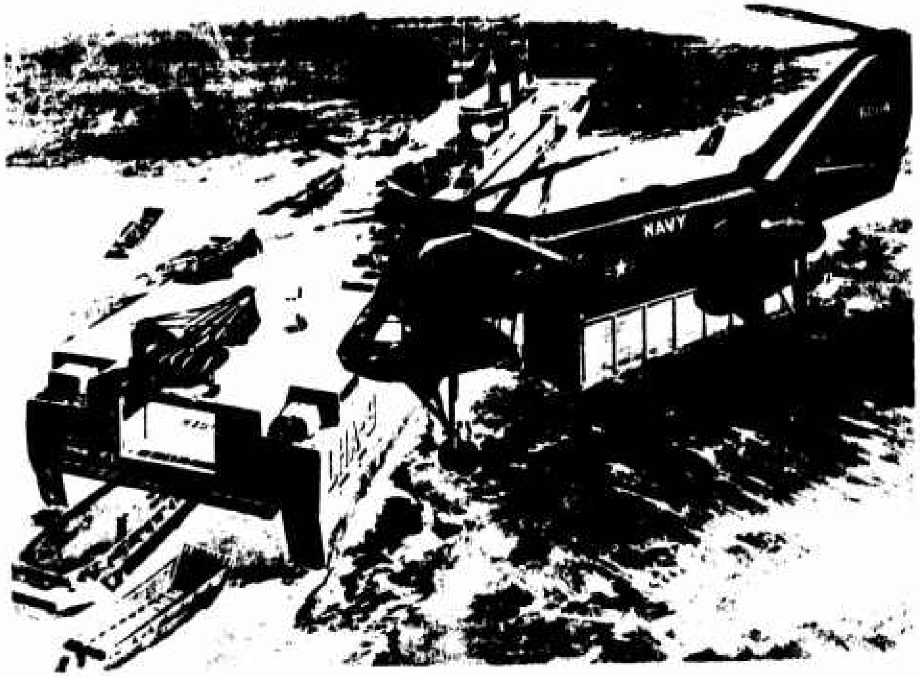
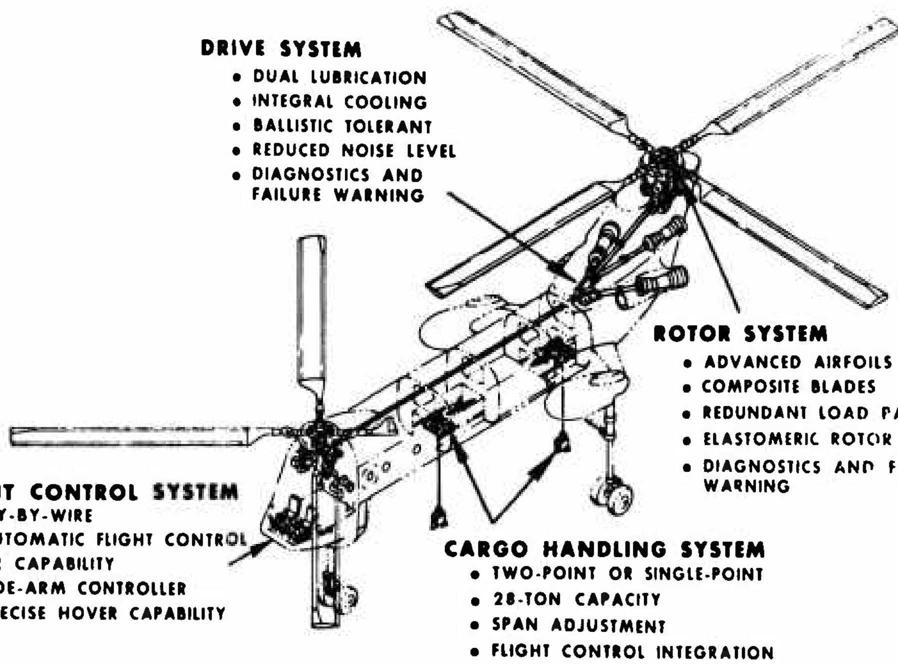


Navy Logistics Support



Weight (lb)	
Design Gross Weight	118,000
Design Payload	45,000
Design Mission Fuel	11,080
Fixed Useful Load	2,340
Empty Weight	59,580
Max Alternate Gross Weight, LF = 2.0	148,000

They have formed their own association – The Helicopter Association of America – to which most belong. The association includes both a safety officer and a safety program, and fosters such committees as the Heavy-lift Committee, through which it strives to improve its techniques and the effectiveness of its various operators.

Most of the commercial helicopters flown are smaller than current military cargo helicopters. However, one operator routinely uses a CH-54 in a logging operation in California. CH-54's are an integral part of the Alaska pipeline installation plan. The HLH plays an integral part in consideration of future commercial requirements. The external cargo carriage of the commercial helicopter represents an important facet of the helicopter's future. The history of this commercial experience is also important to the conclusions of this study.

C. PROBLEMS IN EXTERNAL CARGO CARRIAGE

In the early developmental years – in particular, from 1955 to 1970 – the helicopter's intrinsic capability to carry external cargo outpaced the development of complementary equipment, materials, and personnel capabilities. While the Army helicopter pilot is relatively well trained, probably no amount or quality of other than on-the-job training would prepare him to cope with the diversity of loads, combat operational pressures, and varied terrain of true combat support conditions. External loads can be extremely difficult to carry. Load stabilization, especially for low-density loads, can be extremely difficult, even for a highly experienced pilot. High-density loads, in combination with dynamically mismatched rigging, have often induced collective vertical bounce with which even the most experienced pilot frequently cannot cope. The act of connecting and picking up an external load from a hovering position requires excellent coordination between the pilot and the air crew – the pilot's visibility alone is inadequate.

Material failures, however, have predominated. Early slings were principally nylon air drop units. Nets used were those designed for shipboard and ground application. Early cargo hooks were modifications of bomb release mechanisms. Few of these original materials have proven to be fully suitable for the more severe stress, fatigue, and abrasion requirements of external cargo-carrying.

Material failures of rigging materials in the hands of ground troops probably represent the largest category of failures. These failures are highly dependent on the ground troops' capabilities to select, inspect, and apply rigging properly. Certain artillery and engineer divisions had some training in rigging for external carriage before combat assignment. In most units, however, the responsibility for such training was left to the individual unit commanders to be administered during their assignment. It is not then surprising that the performance of these ground troops in this application has varied dramatically.

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Compounding the problem is the intrinsic difficulty in inspecting woven rigging materials, particularly synthetic ones. The "as-manufactured" strength variations of these classes of materials have historically been large. Visual inspections can and do detect gross flaws of significance, but to date there is not even a validated laboratory nondestructive test for residual strength. These materials can be severely degraded with little evidence of gross flaws. Conversely, some superficial observations, such as some severe stains, may have little correlation with strength degradation. The same observations to a lesser degree hold true for metal-rigging materials. Ground troops who function in a mobile environment exposed to the elements are ill equipped to cope with the care and inspection of rigging materials.

In the late 1960's the Army Air Mobility Research and Development Laboratory and many others began programs of systematic analysis of material failures. External loads were modeled and dynamic loadings determined. Programs leading to a better understanding of the properties of applicable rigging materials were undertaken. At this point in time, facing the accelerated development of heavy-lift helicopters (HLH), studies of the effects of these properties and conditions have also been accelerated. This study represents perhaps the first systematic system analysis of all the elements of unreliability that have compromised the performance of these systems in the past.

D. REASON FOR FOCUS ON VIETNAM EXPERIENCE

Insignificant amounts of external cargo were carried by the military before 1965. The helicopters of paramount interest to external cargo carrying and the procedure itself were concurrently developed in the time frame from 1965 to 1971. These aircraft are principally the Army's CH-47 and CH-54 and the Marine Corps' CH-46 and CH-53. Their cargo-carrying experience has predominantly occurred in Vietnam. Since Vietnam is a conflict rather than a declared war, their experience during this stressful exposure is both unique and doubly important.

We are principally, but not exclusively, interested in the "real world" worst-case experience with these systems as opposed to laboratory or training experience. Only by looking at what happens in this environment can we identify the real weaknesses in the system. These weaknesses may not be apparent in any other less stressful or simulated experience.

We want to know what breaks down under stressful conditions – equipment and/or people? And we need to know all the permutations of system limitations. While such data from a conflict are limited and hard to deal with, it is the only data that can give us the answers we need.

II. PROGRAM OBJECTIVES AND SCOPE

A. OBJECTIVES

The principal objective of this study was to identify, develop, and subsequently recommend cost-effective corrective actions that could be expected to significantly attenuate failures and increase the productivity of current helicopter external cargo-handling systems. A second objective was to extrapolate current system findings to identify potential problem areas in future heavy-lift systems.

B. SCOPE OF WORK

The scope of work proposed consisted of nine principal tasks, each of which is described below.

1. Overview of Helicopter External Cargo-Handling Operations

We proposed to obtain system-wide data to provide a better understanding of the overall operational context in which helicopter failures occur. These general data were to include, but not be limited to, information relating to the size of the inventory of helicopters of interest in this study; the number of pilots and flight and ground crews trained each year; the number of missions and hours flown by type of helicopter and cargo (aircraft recovery, fuel delivery, ammunition delivery, etc.); the probable value of cargo carried and cargo lost, total and by type; the failure rate on a permission basis by type of cargo; and value of the various types of helicopters specified for this study.

This type of data was to be important in establishing the relevance and significance of the various types of failures (for example, failure to deliver badly needed ammunition to a combat area may be more significant than failure to move a disabled helicopter from a secured area to a maintenance depot), the failure rate on a per mission basis for specific types of system failures, the total value of cargo lost on a system-wide basis, the probable system-wide cost of taking a specific corrective action, and so forth. This type of information was thought to be essential in putting failures and potential corrective actions in perspective.

2. Literature Search

A literature search was to be conducted to identify all government and industry data sources and reports which were relevant to this study. Of particular interest were studies on cargo-handling procedures, failure reliability data of the system and its components, the dynamics of helicopters' externally carried cargo systems, pilot handling quality analysis, and so forth. This literature search was to support the data gathering described in the tasks below.

3. Sample Documented Failure Data Base

The initial step in gathering documented failure data was to sample the sources to determine the nature and extent of the data available. This was thought to be an important task since knowledge of the nature and extent of the data available was necessary in planning the details of a comprehensive data-gathering effort. We planned to gather data on the system, function, mission, failure mode, and cause.

At a minimum, the components of the external cargo-handling system of the helicopter that were to be considered would include pallets, pods, containers, cargo nets, doughnuts, slings, pendants, cargo hooks, hoist cables, hoists, winches, load isolators, power systems, load release systems (normal and emergency), instrumentation, controls and displays, and the variety of small hardware used in rigging a load (rings, clevis assemblies, link assemblies, and so forth).

We proposed to collect external cargo-handling system failure data on the following helicopters:

The Bell Helicopter Company's UH-1
Boeing-Vertol Division's CH-46
Boeing-Vertol Division's CH-47
Sikorsky Aircraft's CH-53, and
Sikorsky Aircraft's CH-54

4. Formulation of Detailed Data Retrieval Plan

Based on the information obtained in Tasks 1 through 3, we proposed to formulate a plan to retrieve the detailed and supporting consensus data required for failure analysis. The plan consisted of identifying the specific data required and available, developing a data-gathering format to ensure that all pertinent data were retrieved in a consistent manner by all personnel involved, specifying the procedure for retrieval, and establishing a schedule.

5. Data Retrieval

Utilizing the plan developed in Task 4, we planned to retrieve all relevant data (both quantitative and consensus). In addition to gathering failure data from various government and commercial manufacturing facilities, we planned to interview appropriate planning and engineering staff personnel to determine the requirements of external cargo-handling systems of future heavy-lift helicopters and the engineering developments being made to support these requirements. Knowledge of the important design and operational aspects of future systems would be important in projecting probable failure rates and design requirements.

In visits to various Army facilities we also planned to identify how external cargo-handling systems in helicopters were used in combat support in an overall sense. We would determine what the important attributes of the system are or should be. From this information we would then have a better knowledge of those failure modes that have a significant adverse effect on combat support. Additionally, while visting these Army facilities, we would try to get a sense of the relationship between external cargo-handling system failure rates and helicopter performance and productivity.

6. Data Compilation

We would compile the data retrieved in the previous tasks in an orderly, consistent manner which would lend itself to quick access and efficient analysis. At a minimum, the compilation format would be composed of descriptive elements of the system, function, mission, failure mode, and cause of failure.

7. Data Analysis and Presentation

Using the data compiled in Task 6, we would then conduct an in-depth analysis to determine the extent, significance, and probable causes of current helicopter external cargo-handling system problems and deficiencies. This result would then be used to identify cost-effective corrective actions that could be expected to attenuate failures in existing systems significantly and to extrapolate the probable effects of heavier loads (up to 110,000 pounds) proposed for future helicopters s ch as the heavy-lift helicopter.

The results of this analysis would be presented in a manner which clearly supported the conclusions derived and clearly illustrated the significant aspects of external cargo-handling systems such as the modes of failure, measures of reliability, the interrelationships between system problem areas, and the effect of cargo-handling failures and deficiencies on helicopter productivity and performance. The data would be presented in tabular and graphic form. Schematic diagrams illustrating the helicopter external cargo-handling system, with overlays of resultant failure rates by mode, causes, and the like, would also be used where appropriate.

8. Development of Candidate Areas for Corrective Actions

Based on the data analysis and knowledge of the system developed, we would describe and recommend candidate areas for corrective action which have a high probability of significantly contributing to improved total effectiveness of current and future helicopter external cargo-handling systems. These recommendations would be based on identified modes and causes of failure which have resulted in high costs of cargo lost either by high failure rates and/or high costs

per failure. They would also take into account other adverse effects of failures such as personal injuries, inadequate support of combat units, and reduced helicopter performance and productivity. The probable extent and cost of corrective actions for each mode of failure and cause would be estimated and used as part of the criteria in identifying cost-effective corrective actions that should be taken.

Additionally, we would identify those system factors which are adversely sensitive to cargo weight and the type of cargo-handling techniques which will be utilized on future heavy-lift helicopters, such as the HLH. We would also project the degree of adversity, such as probable failure rates and costs of losses, given the probable technology and operational concepts that will be employed.

9. Development of Corrective Actions

Finally, for the candidate areas developed, we would perform a more in-depth analysis, although not necessarily a detailed analysis, of the corrective actions and procedures that should be taken to minimize the recurrence of significant problems identified for current and future helicopter external cargo-handling systems. We anticipated that the resulting corrective actions proposed would vary in technical depth, ranging from recommending very specific detailed corrective actions to an actual research effort. The specifics of the recommendations would depend upon the complexities and uncertainties of the problem.

We would also analyze relevant component hardware and operating procedures of the system, and recommend specific cost-effective actions that have the potential of significantly improving the total effectiveness of current and future helicopter external cargo-handling systems. The recommended actions would be in the nature of improvements in concept, design, specifications, testing, maintenance, operating procedures, and training. In support of this task we conjectured that we might have to visit component manufacturers to obtain detailed information on components they manufacture if these components are found to be deficient.

C. SUBSEQUENT MODIFICATIONS TO SCOPE OF WORK

By the fourth month of the contract, it became obvious that the data available were not comprehensive enough to fully support all the objectives of the program. A complete search of principal documented records did not disclose data that were specific as to causal factors and stress on the system causing failure. Operational data from Vietnam were found to be almost completely unavailable from any source. Likewise, the consensus data and failure descriptions gathered from pilots and air crewmen, while extremely helpful, were also not completely specific. For many of the variables, the consensus data from the

same person were not consistent. In fact, we found that the same question asked two different ways often received two completely different answers, depending on whether the question had emphasized equipment or people. Moreover, the consensus data often did not support the documented data.

During the fifth month of the contract, certain conclusions were reached; in summary, our analysis could not be so quantitative as we had originally planned. Specifically, the data would not support a completely quantitative analysis of the following contributions to the causes of failures:

- Human error vs. unjustifiable mechanical failures,
- Effects of pilot-induced oscillations,
- Effects of unstable loads,
- Human error vs. supply/logistics deficiencies.

Commensurately, the data would not allow a completely definitive and quantitative analysis of:

- Design or qualification testing and specifications,
- Maintenance,
- Training, and
- Improper work stations.

We therefore proceeded with a more qualitative analysis of these areas of concern than had originally been planned.

Moreover, our analysis proceeded along a less logical task sequential plan than had been originally proposed. We began early to compile the interim report which highlighted the most glaring questions and inconsistencies. We addressed these issues by calling known sources for additional data and re-researching data on hand in order to make the best possible resolution of these uncertainties.

Our hope, then, is that while this report is not so fully quantitative as originally planned, it may place all the issues in proper perspective. If we succeed in imparting to the reader an accurate sense of the history and the dimensions of the unresolved issues in external cargo-carrying systems, this report, we feel, may do much to further their development.

III. DATA SEARCH AND COMPILATION (TASKS 1 and 2)

A. DEFINITION OF AN EXTERNAL CARGO-HANDLING SYSTEM

The word system is derived from the Latin word *systema* meaning to bring together or combine. Its most common definition is:

> *a complex unity formed of many often diverse parts subject to a common plan or serving a common purpose.*

In engineering, a system is typically taken to be machinery/materials and human control functions acting in concert.

Following this definition the functional parts of an external cargo-handling system may be considered to include:

People	**Equipment and Materials**
• The pilot	• The external cargo-handling rigging materials – slings, pendants, etc.;
• The air crew	• The cargo itself – CONEX containers, eyebolts on equipment, etc.;
• The ground crew	• Certain cargo-related parts of the heli-copter – the hook, the controls, etc.

It should be noted, however, that these parts function as a system only when they are actively serving the common purpose of handling external cargo. These relationships are shown in Figure 13. Figures 14 and 15 picture the external cargo-carrying systems of the Army's two current principal cargo helicopters – the CH-47 and CH-54.

It then follows that an external cargo system failure is any occurrence – due to adverse interreactions of the component parts of the system – that results in significant damage to the cargo or the helicopter or injury to the personnel involved.

Note that this definition excludes certain losses such as those caused by engine failure, ground fire damaging the aircraft, and the like. While these are certainly failures, they are not failures of the external cargo-handling system; i.e., the presence of external cargo did not influence their occurrence.

B. HOW THE SYSTEM FUNCTIONS

As shown in Figure 13, in assessing system failures it is important first to understand how the system functions. In all of the instances we will analyze, loads

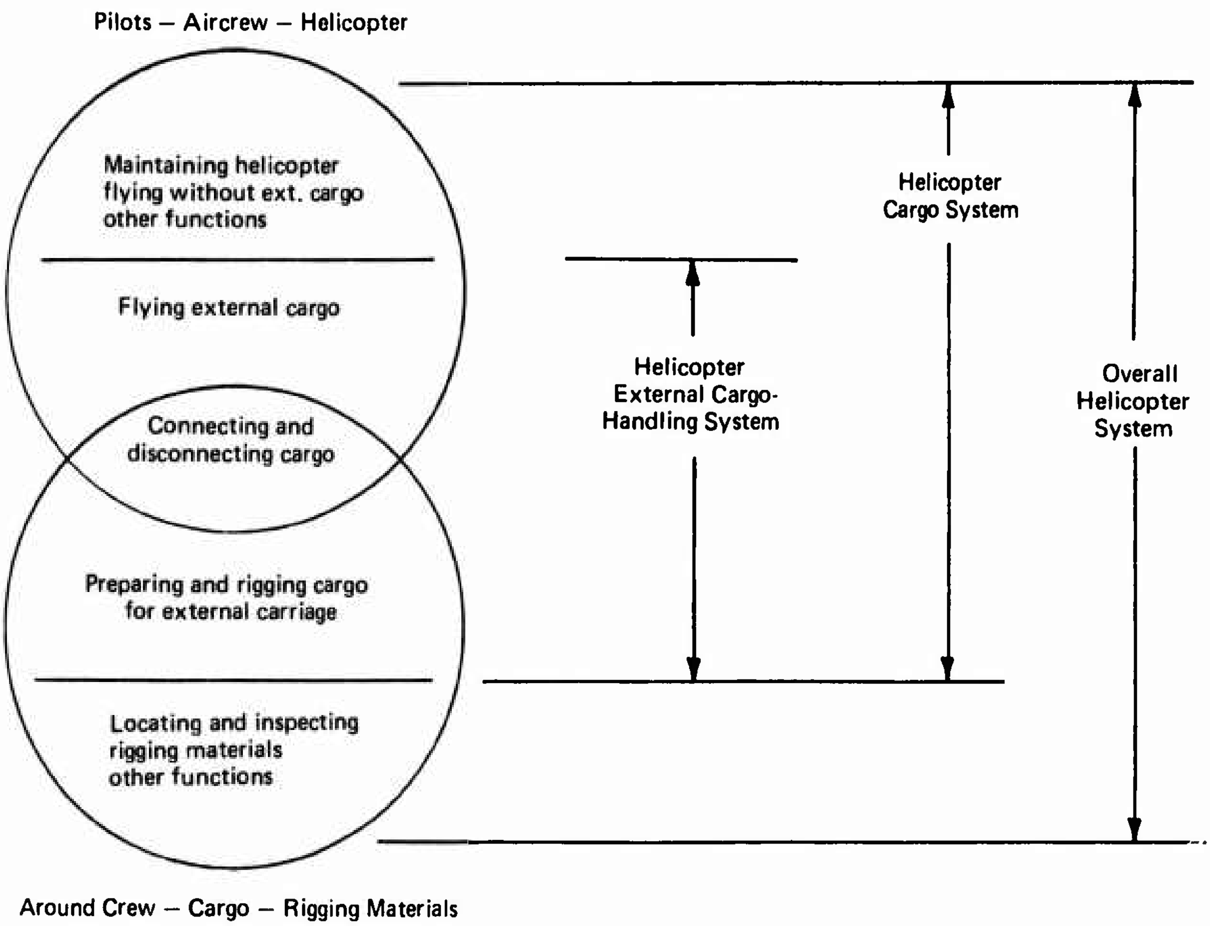


FIGURE 13. RELATIONSHIPS OF EXTERNAL CARGO-HANDLING SYSTEM.

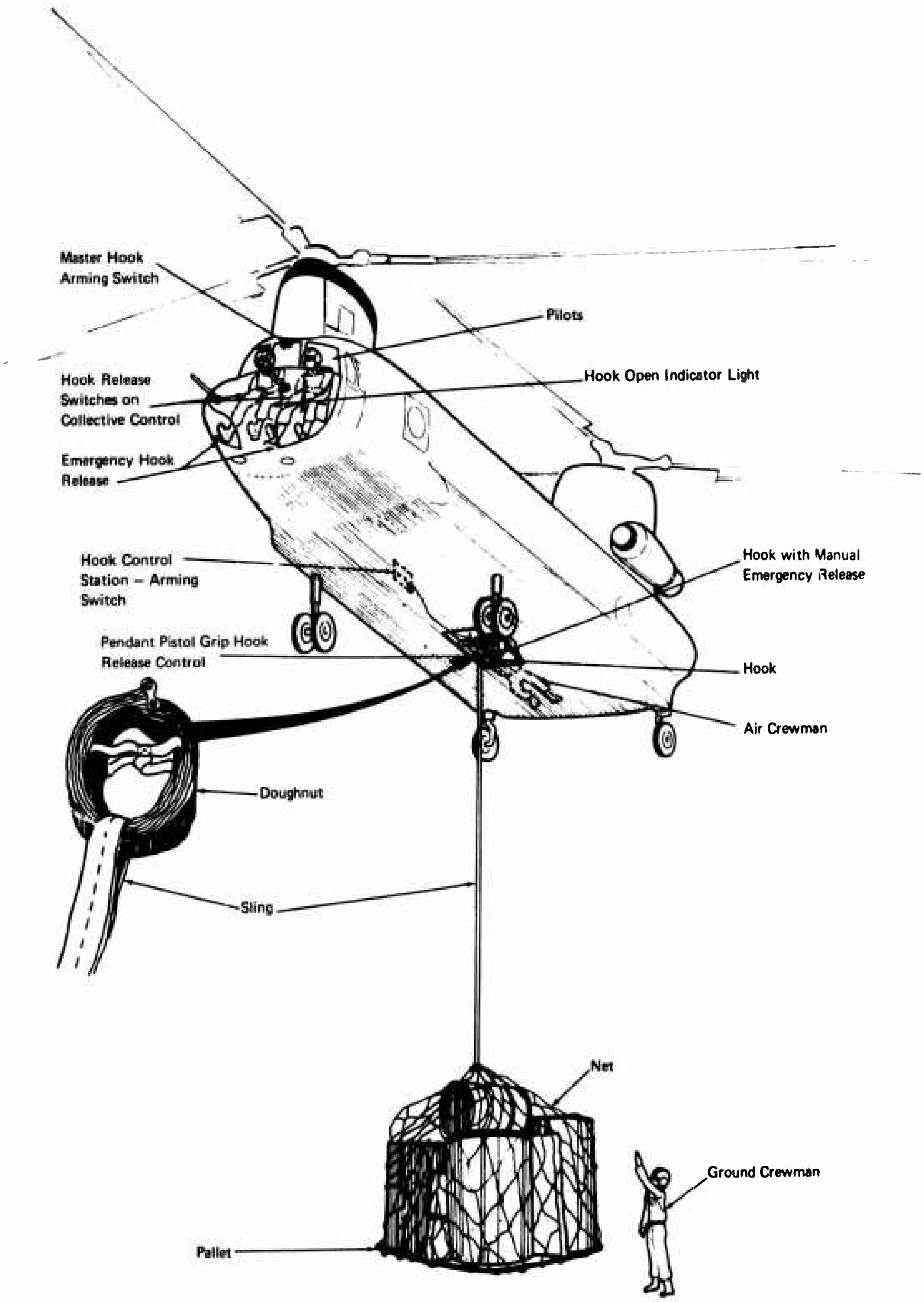


FIGURE 14. THE CH–47 EXTERNAL CARGO SYSTEM.

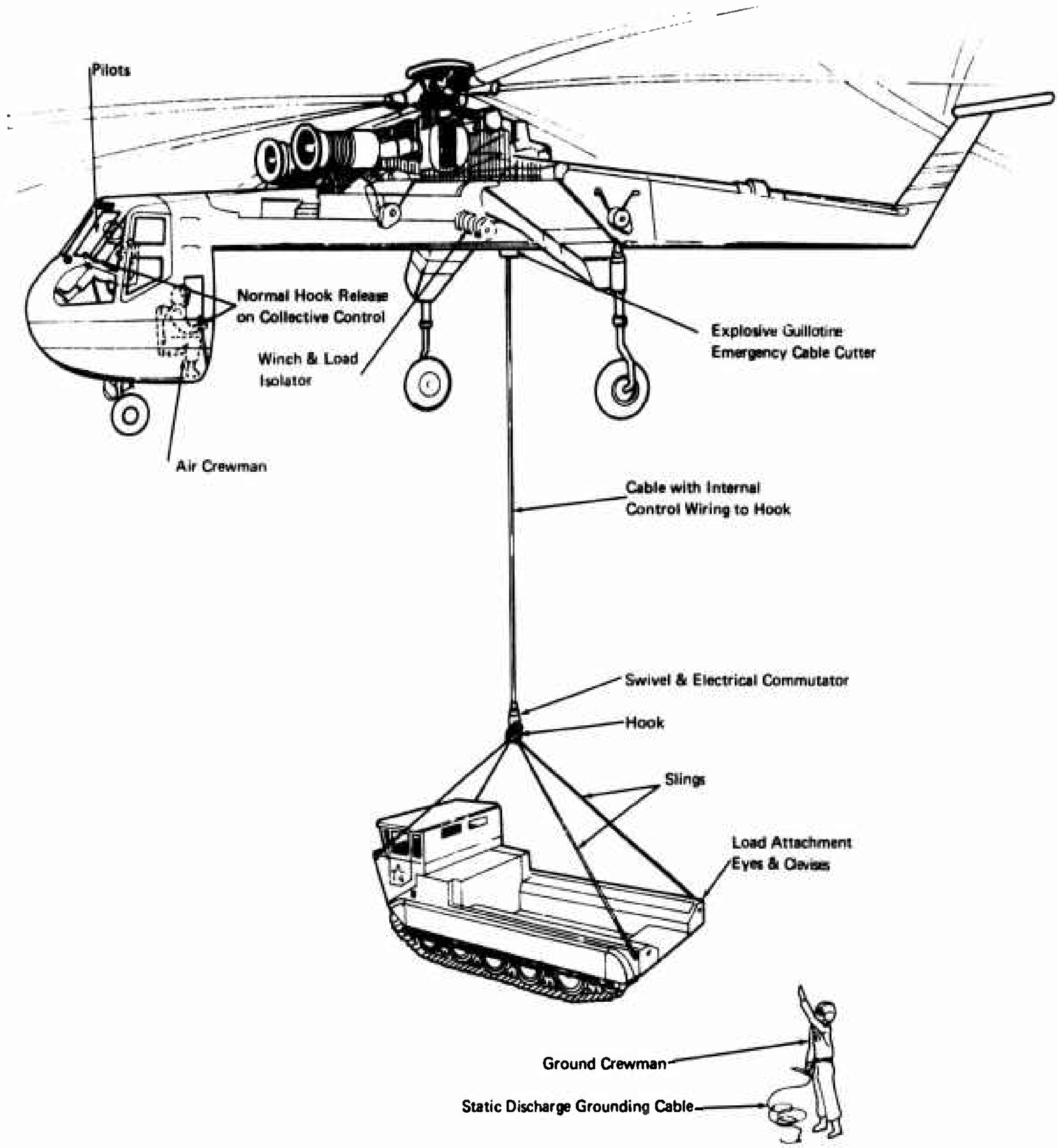


FIGURE 15. THE CH–54 EXTERNAL CARGO SYSTEM.

are picked up from a hover position. The CH-54 has external carriage capabilities while landed, but these are of minor importance (infrequently used) to our study.

The involvement of the air crew and the helicopter in the system really begins at the pickup hover and ends at the delivery hover. The involvement of the ground crew in the system begins earlier when the load is prepared and rigged for external carriage.

At the hover, the pilots and air crewman act in concert to position the helicopter accurately over the load. In the case of the CH-54, the air crewman may do this alone. A ground crewman at this point in time is typically positioned on top of the load ready to place the doughnut or clevis connection to the sling(s) in the hook of the helicopter. A substantial static charge often is present in the helicopter, so the ground crewman must protect himself against its effects. While no one probably has been killed by this charge, ground crewmen have frequently been injured when knocked off the load, or even had their fingers burned by the charge. Heavy insulating gloves and a helmet are worn. Frequently a grounding rod is set up. Sometimes the load connection is effected by the crewman from the ground using an insulated pole, obviating his standing on the load. Frequently the air crewman also uses a pole to assist in this operation.

Once the connection is made, the air crewman notifies the pilot, who commences lift-off. Lift-off is straight up until the aircraft has sufficiently cleared ground obstructions. Then a translation to both a moderate forward speed and climb are undertaken simultaneously.

When sufficient altitude has been achieved, the pilot changes his pattern to level flight at a greatly increased airspeed. This is a critical part of the flight, since the load is largely an unknown quantity to the air crew in terms of aerodynamic qualities and structural integrity of the rigging. As the airspeed is increased, dynamic stresses on the load and rigging increase to maximum values which may be more than three times static values, and aerodynamic load stabilization problems also may occur. The pilot may have to reduce his airspeed, make turns, and the like, to deal with load-stabilization problems.

Breaking level flight and descending to a hover at the delivery end of the flight are largely the reverse of picking up. Human errors peak during picking up and delivering. Coordination/communication problems are the principal cause. Theoretically a ground crewman standing ahead of the helicopter guides the pilot to the pickup and delivering positions. The aircraft may also be in contact with a radioman on the ground. As a practical matter, neither of these means of communication has proved reliable to the pilot. They are largely ignored, and for this reason we have not assigned the ground crew any responsibility in aircraft guidance.

C. OPERATIONAL PARAMETERS DEFINED/EXPLAINED

The basic operational parameter of a helicopter is measured in terms of sorties. Therefore, to understand our subsequent analysis of operational data, a reasonably precise definition of the term is necessary.

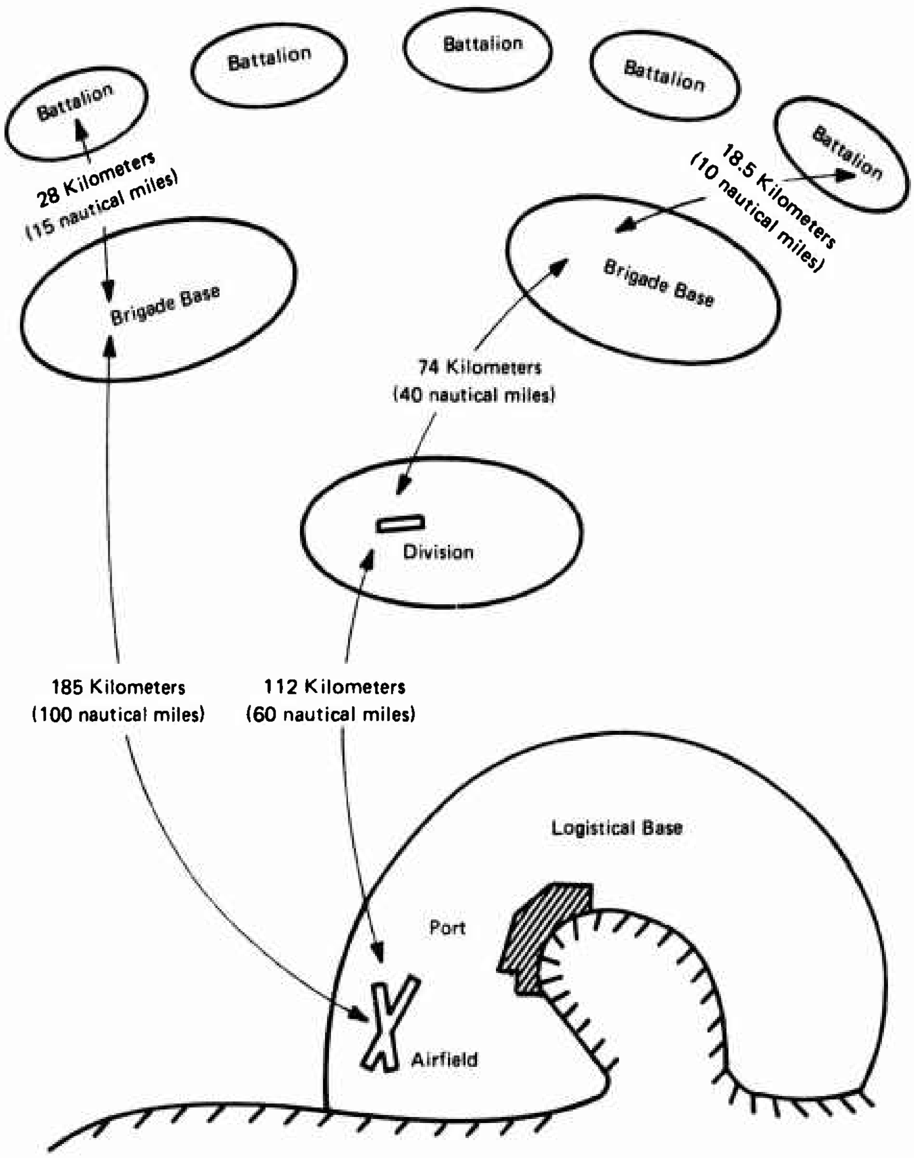
Unfortunately, a precise, universally applied definition of the term does not exist in the military. Moreover, it is obvious from our conversations with Army and Marine Corps pilots that disparate and sometimes changing definitions were used in Vietnam. Therefore, we have found it necessary to establish for the purpose of this study a definition that is reasonably consistent with the data. This definition is simply that:

> A sortie is synonymous with the flights, landings, or hovers of a single helicopter – any flight between two points.

A number of terms, such as mission, tasks, landings, loads, backhauls and the like, are sometimes used to describe other operational parameters. Attempting to define these, we feel, would be a herculean task, recognizing that they are expansions or component parts of sorties whose definition suffers from the forenoted ambiguity. For this reason and because a more precise understanding of all these terms would add little to our analysis, we shall, as far as possible, avoid burdening the reader with their definition or use.

A sortie then is a single-helicopter, single-flight subprogram of the total work program (mission) that a company or squadron will undertake that day. However, single sorties are a rarity and series of sorties are generally the rule. The reader may require a little additional help in envisioning just how sorties fit into the real world of helicopter combat support.

Figure 16 depicts schematically the classical (text book) way in which a cargo helicopter might operate in an underdeveloped area such as Vietnam. The figure, we feel, is relatively self-explanatory. What should be noted is that the average cargo helicopter would probably perform most of its sorties out with the battalions and the brigade base. Most of the sorties would be short, perhaps less than 30 miles, and require on the order of 20 minutes each. Frequently, they are sequential from battalion to battalion or circuitous if a batallion is being moved. Only every hour or two would a helicopter typically have a flight of 100 miles to and from the airfield for refueling.



Source: FM-55-40, Army Combat Service Support Air Transport Operations

FIGURE 16. COMBAT SERVICE SUPPORT FROM A LOGISTICAL BASE TO A COMBAT FORCE OPERATING IN AN UNDERDEVELOPED AREA .

The cargo helicopter company or squadron will attempt to utilize the payload capacity of its helicopters to the maximum safe limit. Thus, helicopters will typically be highly loaded during one sortie and then will return (second sortie) with empty water trailers, containers, and the like, to avoid returning empty. Because of this we find the average payload utilization of these helicopters to be a fraction of their maximum payload.

D. CRITERIA FOR ASSESSING FAILURES

Early in the program we realized that data on specific failures available to us would not be comprehensive. Failure descriptions, in general, lacked complete and penetrating assessments that would allow us to determine fully the root causes and their interrelationships. Typically, these failure descriptions contained only superficial explanations of what happened. For this reason and in order to make the maximum and most objective use of this incomplete data, we had to establish rigid rules for assessing failures. Six basic rules predominate:

1. In failures involving a series of causative events, only the initiating event is counted; i.e., if a pilot error can reasonably be interpreted as initiating a mechanical failure, the mechanical failure is ignored and the failure is counted as pure human error.

2. Where the root cause of the failure is in question, all plausible causes are counted.

3. The air crewman is responsible for the generic-to-the-helicopter equipment in the system. Where equipment failures are clearly stated as caused by inadequate maintenance, this is counted as human error on his part. However, where the reason for specific failures of this equipment is not clearly delineated, the air crewman and the specific piece of equipment itself are both counted as the cause.

4. Similar to the logic in 3 above, the ground crew is responsible for the rigging and load attachment. He is charged with human error for inadequate maintenance or application. Indeterminate descriptions as to cause are dually counted as ground crew error and mechanical failure.

5. The pilot and air crewman are held dually responsible for guidance/visibility problems resulting in damage to the bottom or rear of the helicopter or the load.

6. All other responsibility for failures is assigned to the pilot.

We also found it necessary to assess where failures occurred in the flight (sortie) progression and the density of the load being carried at the time of failure.

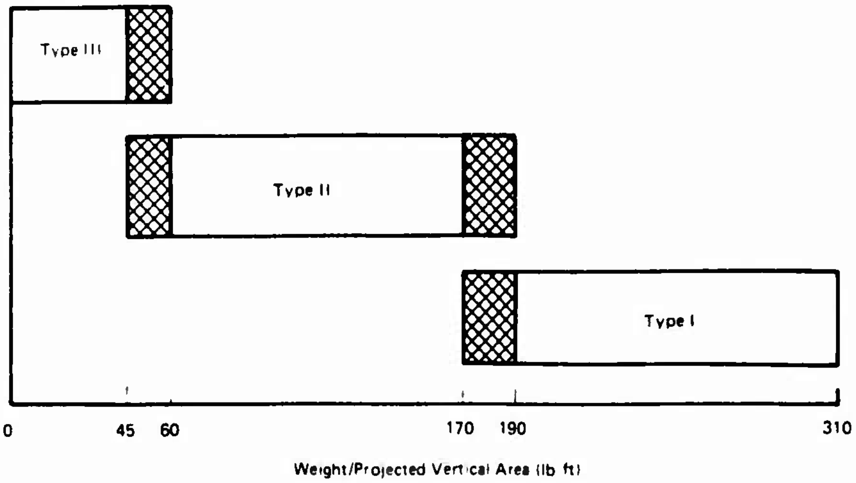
Flight progression determinations are made as follows:

- The aircraft is judged to be *picking up* from the point of load attachment until it reaches level flight.

- The aircraft is judged to be *delivering* from the point where it starts its final descent into the loading zone (LZ) until the load is disconnected.

- The aircraft is judged to be *cruising* in all the remaining portions of the sortie.

Load densities are segregated into three classes using the Sikorsky design guide criteria of load weight per square foot of projected area factors. The three classes are shown in Figure 17.



Source: U.S. ARMROL Tech. Report 22-36

FIGURE 17. TYPES OF LOADS BY WEIGHT/PROJECTION AREA.

E. DATA SOURCES AND SEARCH PLAN

We proposed – and the program actually followed – an approach of identifying gross parameters (overview data) of the whole world of external cargo-carrying and then focusing on the specifics of the problem using this knowledge as background. In identifying overview data, the Office of the Director of Army Aviation was extremely helpful in identifying numbers, deployment,

and costs of helicopters. They advised us on currently active helicopter companies and were helpful in identifying other agencies that might have useful data. A complete list of agencies contacted is given in the appendix of this report.

The U.S. Army Aviation Systems Command (USAAVSCOM) in St. Louis, Missouri, provided invaluable data on aircraft operational utilization through their RAMMIT-AOPU system. They also provided helpful management summaries on some helicopters.

The airframe manufacturers themselves constituted a very valuable source of overview data. Each of these manufacturers had field service representatives in Vietnam. Through the collective efforts of these people, we were able to secure invaluable data on numbers of aircraft, hours, sorties flown, and the like.

Simultaneously with our efforts in the overview area, we started a comprehensive literature search. The principal thrust was exerted through the Defense Documentation Center in Alexandria, Virginia. Through a key word index they provided us with a bibliography of all the applicable Government reports. We also searched through our ADL literature search system for other scientific articles, books in print, and the like, as well as the Failure Rate Data (FARADA) System for related component reliability data. A complete bibliography of these data is given in the appendix.

Following the gathering of overview data and starting the literature search, we sampled the documented external cargo system failure data. For the Army this was done at the U.S. Army Agency for Aviation Safety (USAAVS) at Ft. Rucker, Alabama. For the Navy/Marines this was done at the U.S. Naval Safety Center at Norfolk, Virginia.

Our sampling of the documented data found them to be inadequate for our purposes. For this reason we formulated a data retrieval plan and formats that relied heavily on consensus data and failure reports gathered by personal interview. These plans and formats are presented in the following sections of this chapter.

F. FAILURE DATA RETRIEVAL

Failure data retrieval was one of the most important aspects of our analytical plan. We wished to document as many specific failures as possible in such a way that many cross correlations could be made: load density to sling failures, lift-off to hook failures, and so forth. This necessitated identifying the important variables in the failures as accurately as possible and coding them in such a way that a great many correlations could subsequently be efficiently made. After some investigation, we decided to tabulate these data on McBee® edge notched cards. The final format is shown in Figure 18.

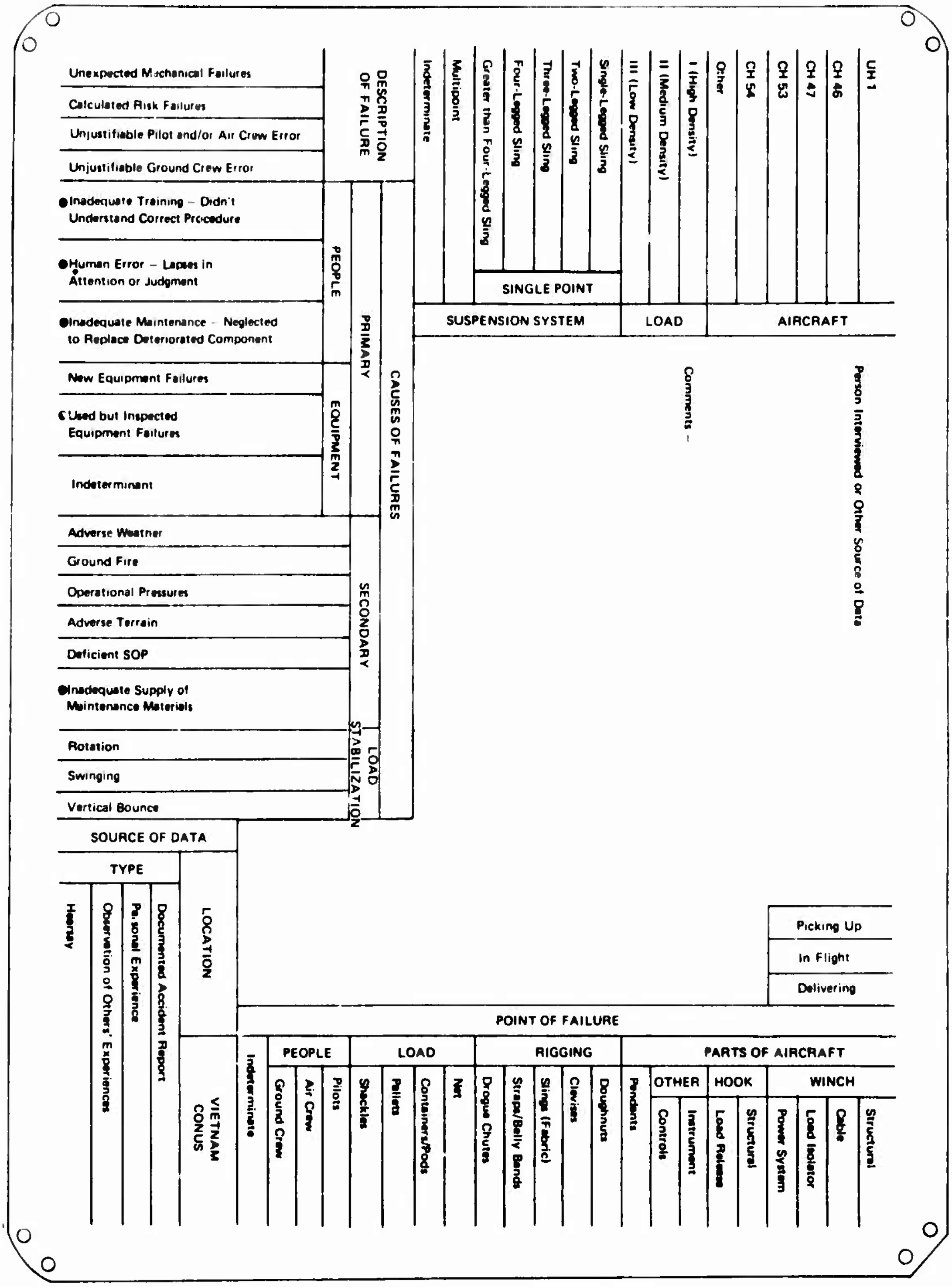


FIGURE 18. FAILURE DATA RETRIEVAL CARD.

Both documented and personal interview data were tabulated on these cards. Navy data retrieved were all documented, and the data from computer runoffs were appraised and entered on these cards as well. We should emphasize that we found it necessary to adhere strictly to the criteria for assessing failures given in Section B of this chapter. We found early that it was not only possible but probable that failure reports could be interpreted quite subjectively. This subjectivity was dependent on the wording or verbal description of the report. For instance, reports often alluded to responsibilities that were only remote possibilities, but it was easy to be so persuaded in the tedium of tabulating cards. In the end we tabulated the data very rigidly and read nothing into it that did not conform to the criteria.

Some of our most valuable failure data was acquired by personal interview. Ninety-four out of 325 failure reports are of this type, and they are the most comprehensive. In these tabulations we sat down with pilots and air crewmen and talked with them through complete descriptions of failures they had either experienced or observed.

G. CONSENSUS DATA RETRIEVAL

Another form of data used was based on consensus. In acquiring data of this type, interviewees are asked to estimate, or even guess at, the magnitude of a parameter in a field with which they are experienced. If there is a reasonable correlation in a significant body of such data, the data are justifiably held to be valid.

In some quarters such data are suspected and considered unscientific. Some reflection, however, will convince most of its great value. For instance, if 100 pilots agreed that their companies experienced 10 failures a month, but the documented data showed 2 failures a month, which would be considered the better data? It is obvious, we think, that the documented data would have minimum value, while the consensus data could be considered more realistic. Since failures can compromise one's record, a pilot is unlikely to report more than he experienced, but might very well report less.

Consensus data generally, and in this case, were used to:

- Resolve uncertainties in the documented data; and
- Uncover areas the documented data would not or did not cover.

Our consensus format, as for most of our other data, was focused on Vietnam. It was also focused on seven basic overall operational parameters of a given helicopter flown there in external cargo-carrying:

1. Number of sorties flown daily,
2. Number of hours flown daily,
3. Overall failure rate,
4. Distribution of load types carried,
5. Failure rates vs. load types,
6. Distribution of mechanical failures, and
7. Differentiation of mechanical vs. human error failures.

Our consensus questionnaire is shown on the following pages.

HELICOPTER EXTERNAL CARGO-HANDLING QUESTIONNAIRE

The Army Mobility R&D Laboratory at Ft. Eustis has contracted with Arthur D. Little, Inc., of Cambridge, Massachusetts to analyze the reliability of helicopter external cargo-handling systems.

The principal objective of this study is to recommend cost-effective actions that will reduce failures in current systems, and to extrapolate current system findings to identify potential problem areas in future heavy-lift systems now under design.

A most important source of data in performing the study will be the estimates and opinions of experienced personnel. Such data are necessary to augment documented data which are not expected to be completely adequate for our reliability analysis. This questionnaire solicits these estimates and opinions. Your cooperation in filling it out will be most helpful to the successful completion of the work.

DEFINITIONS

What are the functional parts of an external cargo-handling system?

They are:

People	**Equipment and Materials**
• The pilot	• The external cargo handling rigging materials – slings, pendants, etc.
• The air crew	• The cargo itself – CONEX containers, eyebolts on equipment, etc.
• The ground crew	• Certain cargo-related parts of the helicopter – the hook, the controls, etc.

What is a system failure?

Any occurrence due to adverse interreactions of the component parts of the system that results in significant damage to the cargo or the helicopter or injury to the personnel involved.

Note that this definition excludes certain losses such as those caused by engine failure, ground fire, and the like, because the engine and enemy troops are not considered part of the system.

VIETNAM EXPERIENCE

Would you describe the overall experience of the units to which you were assigned?

Were you: a pilot ( ), air crewman ( ), other ____________________( ).

	1st Assignment	2nd Assignment
• Unit	________	________
• Location	________	________
• Time period engaged in flying operations	________	________
• Type and model of helicopter flown	________	________
• Average (typical) number of helicopters that were flown daily	________	________
• Greatest number of helicopters ever flown by the unit in a single day	________	________
• Average (typical) number of sorties flown by each helicopter daily	________	________
• Greatest number of sorties ever flown by a single helicopter on a single day	________	________
• Approximate number of instances of external cargo failures (drops, damage, injury) the unit experienced monthly	________* (Please enter these numbers in the designated block on bottom pg. 39)	________**
• How many active pilots were there in the unit	________	________

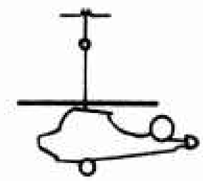
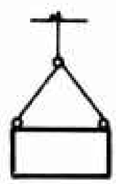
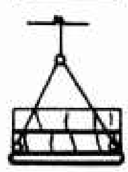
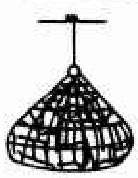
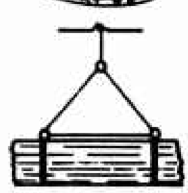
VIETNAM EXPERIENCE (Continued)

Would you describe your personal experience in the unit?

	1st Assignment	2nd Assignment
• What was your average flying time per month	____________	____________
• How many days a month did you typically fly	____________	____________
• How many hours a day did you typically fly	____________	____________
• How many sorties did you typically fly on a given day	____________	____________
• What was the greatest number of hours you ever flew in a day	____________	____________
• What was the greatest number of sorties you ever flew in a day	____________	____________
• What do you think would be the average weight of all the external loads you carried	____________	____________

TYPE LOAD VS. FAILURES

Would you estimate the distribution of types of loads you personally carried and then the associated failures by type from your perception of the combined experience of the company(s) to which you were assigned?

Type Load		Your Personal Experience Sorties per Year		The Combined Experience of Your Company Sorties that Failed in a Year	
		1st Asgmt.	2nd Asgmt.	1st Asgmt.	2nd Asgmt.
1. Disabled Aircraft					
2. Other Single Unsupported Items: Tanks, Trucks, Howitzers, Bulldozers, Fuel Bladders, Etc.					
3. Containerized Loads					
4. Palletized Loads					
5. Loads in Nets					
6. Chained or Strapped-Together Loads					
Total Sorties You Flew in a Year					
Sortie Failures Your Company(s) Experienced in a Year				*	**

POINT OF SYSTEM FAILURE
(Summary of all Experience)

Would you give your perception of how material failures distribute among the categories and subcategories shown?

1. Equipment that is normally supplied as part of the helicopter	____%	a. Winch, Cable, Isolators, and Power System	____%
		b. Instrument and Controls	____%
		c. Hook and Load-Release Mechanisms	____%
2. Rigging	____%	a. Pendants	____%
		b. Doughnuts	____%
		c. Clevises	____%
		d. Slings (Fabric)	____%
		e. Slings (Metal or Chain)	____%
		f. Drogue Chutes	____%
3. Load Attachments and Containers	____%	a. Nets	____%
		b. Containers/Pods	____%
		c. Pallets	____%
		d. Shackles (Directly Attached to Non-containerized Load)	____%
	100%		100%

CAUSE OF FAILURE

We would like your assistance in attempting to assess the cause of failures experienced by your unit in combat. We have selected five categories of failure causes. Based on your unit's combat experience, what percentage assignment is appropriate?

1. Failure attributable neither to mechanical failure, human error, or calculated risk. ______ %

   Examples: Unexpected dust caused IFR conditions at the LZ, sudden and unpredictable wind shifts, etc.

2. Unjustifiable ground crew error. ______ %

   Examples: Human error in rigging or maintenance and inspection of lift materials, underestimating weight of load, etc.

3. Unjustifiable pilot and/or aircrew error. ______ %

   Examples: Exceeding allowable airspeed for bulky or unstable loads, inadvertent jettison of load, carrying too much weight for the density altitude at the LZ, etc.

4. Calculated risk failures. ______ %

   Examples: Missions that must be flown with improper equipment or under severe weather conditions. Exceeding the airspeed restrictions due to ground fire, etc.

5. Unexpected mechanical failures. ______ %

   Examples: Failures occurring when operating within the prescribed envelope with properly inspected equipment.

Total 100 %

IV. DATA PRESENTATION

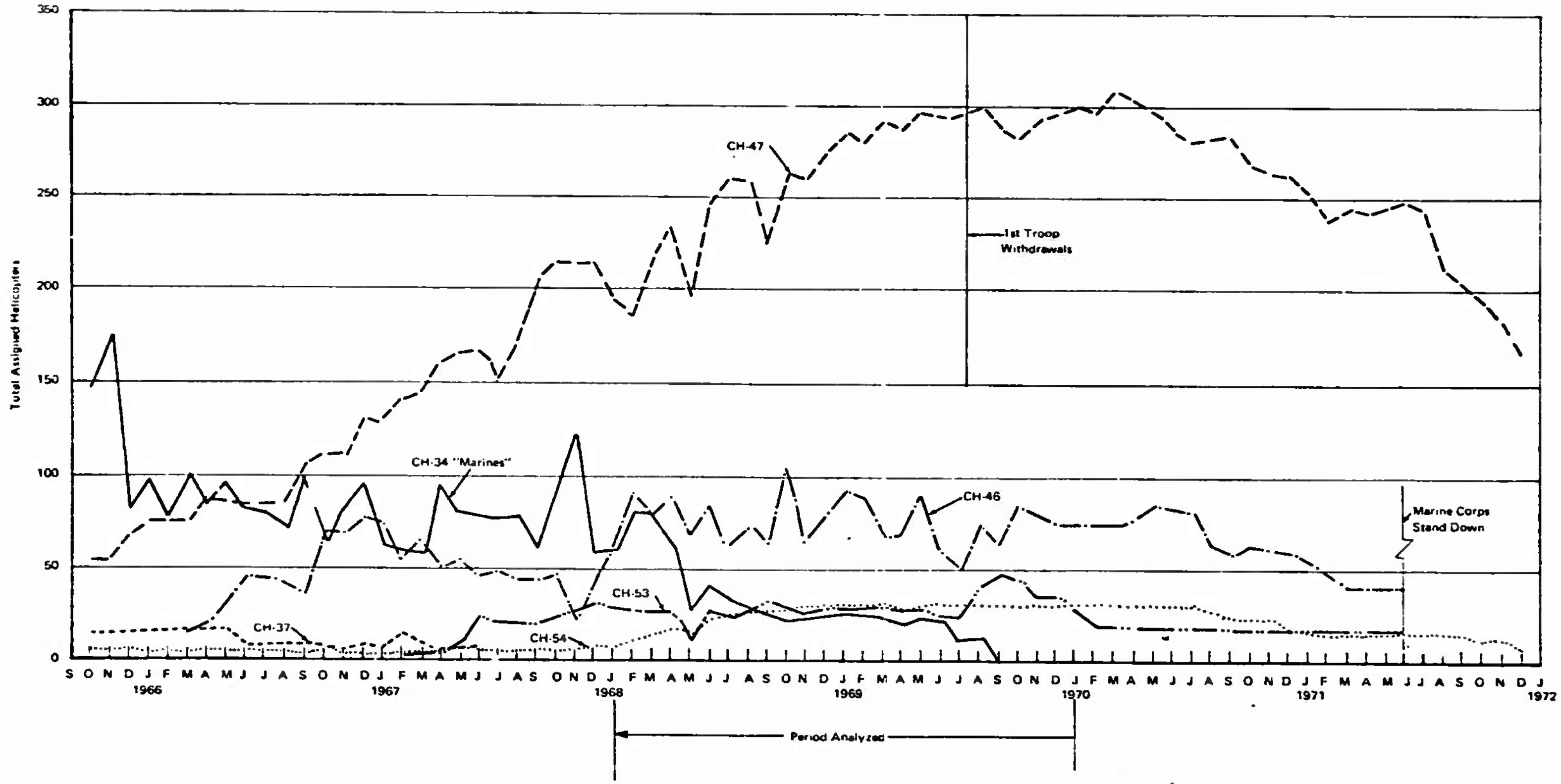
A. INTRODUCTION

In researching for this study, we found that many misconceptions and divergent opinions exist, even among well informed persons concerned with failures in helicopter external cargo systems. Many past studies in analyzing specific causes of failures – for instance, degradation of nylon slings and the like – have warranted considerable technical merit. However, none of which we are aware analyzed all the principal causes of failures and their interrelationships. Similarly, no study has treated the history of the development of helicopter external cargo-handling. One needs a good grasp of the operational differences of the various helicopters and their respective military services to understand fully the reasons for the types and magnitudes of the failures they experienced. A good sense of the history of the development of external carriage techniques is also necessary to appreciate fully the course and momentum of developments currently in progress. No system is static, and this is certainly true of external cargo-handling systems. In fact, many developments are currently under way.

We now believe that one of the most useful outputs of this study will be the placement of all these factors in proper perspective. In particular, we wish to convey an understanding of external cargo carriage in Vietnam. While external carriage originated in Korea in 1953-54, its potential was not fully realized or exploited until the Vietnam conflict. Even by 1966 the practice was little used by the Marines and probably only moderately used by the Army. However, by the 1968 to 1969 period, both services probably carried on the order of 75% of all cargo externally. External carriage in a few short years had become the principal operating mode of cargo helicopters. Since it is a complex procedure, it is not surprising that problems were encountered.

For all these reasons, we will delineate the utilization and failure experience of the cargo helicopter in Vietnam. In particular, we will cover Army and Marine Corps experience in the period from 1966 to 1972, and later we will concentrate on the 1968 and 1969 period when external carriage was at its peak. The helicopter cargo-carrying experience of the other military services in Vietnam was negligible in comparison.

The techniques of external carriage were developed simultaneously by both the military and commercial operators. The latter group was quick to recognize the potential of the procedure for transporting commercial cargo and equipment to inaccessible places. Since the commercial techniques and experience are somewhat different from those of the military, we will also summarize them for comparative purposes.



Source: JCS OPREA File

FIGURE 19. NUMBERS OF ACTIVE ARMY AND MARINE CORPS CARGO HELICOPTERS IN VIETNAM.

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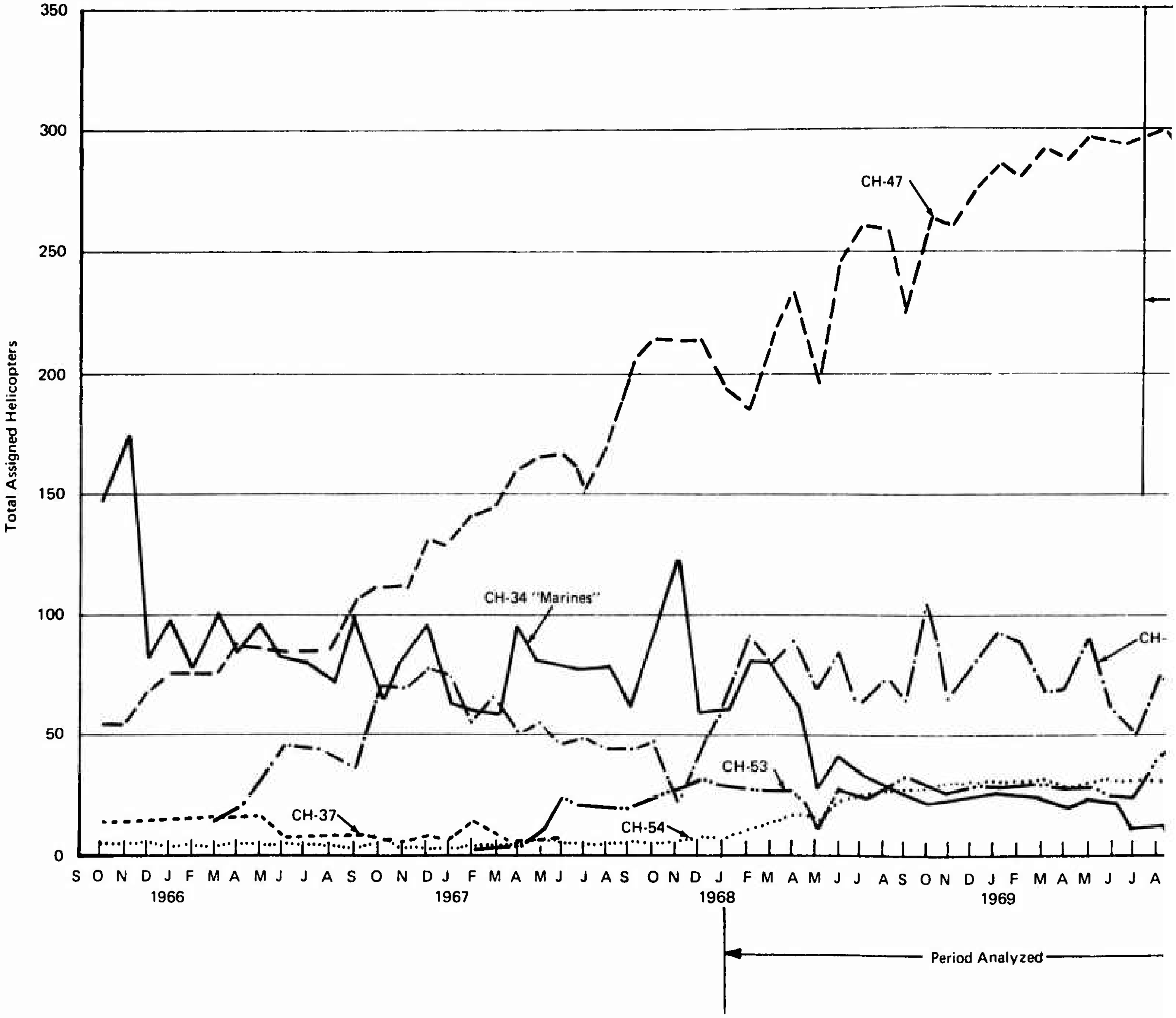

Source: JCS OPREA File

FIGURE 19. NUMBERS OF ACTIVE ARMY AND MARINE CORPS CARGO HELICOPTERS IN VIETNAM.

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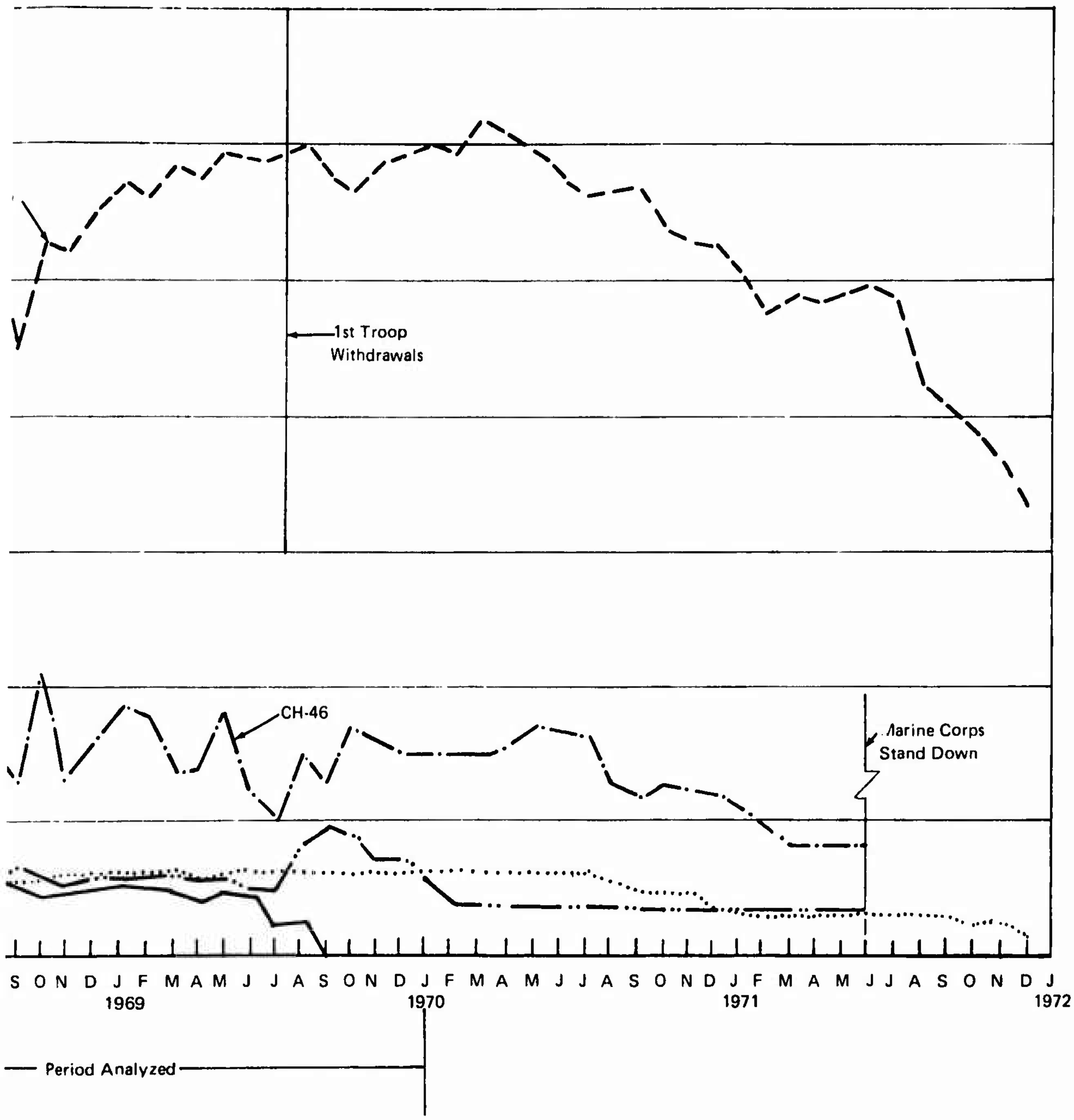

1st Troop Withdrawals
CH-46
Marine Corps Stand Down
S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J
1969
1970
1971
1972
Period Analyzed

B. CARGO HELICOPTERS DEPLOYED TO VIETNAM

Military helicopters deployed to a combat zone are hereafter considered to fall into three categories:

1. Total helicopters;

2. Active helicopters – those used routinely by squadrons or companies, excluding new helicopters awaiting assignment or substantially damaged helicopters stricken from the active list because they require major repair or overhaul; or

3. Combat or mission-ready helicopters – not even minor repairs required – ready to fly.

In effect, we will be dealing with category 2 – active helicopters. We are not too concerned with total helicopters – for obvious reasons – and a combat-ready helicopter would be a moderate integration of active helicopters which would be hard to deal with and would add nothing to our analysis.

The number of active helicopters, particularly in a combat zone, fluctuates dramatically, almost by the hour, the fluctuation being a function of several variables. Helicopters are stricken from the active list due to crash damage or the need for extensive repair or overhaul. New or rebuilt helicopters may be brought in to replace these attritions or to respond to increased demand for their services. Conversely, helicopters may be removed from a zone when the need for their services decreases.

Figure 19 shows the time progression of numbers of principal active Army and Marine Corps helicopters having cargo-carrying capabilities in Vietnam during the period of 1966 to 1972. Two types of helicopters are of interest: the utility helicopter (UH) and the cargo helicopter (CH).

The two services entered the Vietnam conflict flying piston-powered utility/cargo helicopters of Korean vintage, principally the UH-34 and the larger CH-37. In 1963 the jet-powered UH-1 was introduced. Subsequently, the Army employed almost 2200 and the Marines about 77 of these helicopters in Vietnam. While they were the largest fleet of helicopters having cargo-carrying capabilities, they are not shown in Figure 19 because the records show they carried little cargo and negligible amounts of external cargo. Both the Army and Marine Corps had helicopters better suited for cargo carrying. However, the UH-1 proved to have great utility for other than cargo carrying and was used – as its initials implied – as a general utility helicopter. Its two principal missions were in flights as an armed and escort helicopter and in miscellaneous combat support profiles.

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The 1960 to 1968 period was evolutionary for the cargo-carrying helicopter in Vietnam. With the exception of the Marines' UH-34, the piston-powered helicopters were replaced by newer jet-powered CH-46's, CH-47's, CH-53's, and CH-54's. The Marines continued to find the UH-34 useful in Vietnam until late 1969, but not to any significant extent for cargo carrying.

External cargo carriage increased from a minor fraction in 1966 to 75% of total cargo carried in the 1968 and 1969 period. In late 1969, the first troop withdrawals began and the conflict began to lessen. Therefore, we have chosen to analyze, in greater detail, helicopter experience in the 1968 and 1969 time span, particularly that compiled by the CH-46's, CH-47's, CH-53's, and CH-54's. Their physical characteristics and those of the UH-1 are presented in Table II for comparative purposes. Their combined experience in the '68-69 period in Vietnam encompassed an overwhelming majority of all external cargo carried by helicopters there.

1. The CH-46 and CH-47 Helicopters

The Boeing-Vertol CH-46 and CH-47 helicopters are very similar in configuration and appearance, although substantially different in size and payload capabilities. They had the same root beginnings when in 1956 Boeing-Vertol began preliminary design and engineering of a twin-turbine transport helicopter for commercial and military use. Their main objective was to take full advantage of the high power, small size, and light weight of the shaft turbine engines then becoming available. To achieve the best possible hovering performance, rotors were mounted on front and rear pylons, and the turbines were mounted above the rear of the cabin on each side of the rear rotor pylon. This design resulted in maximum unobstructed cabin area and permitted the use of a large rear ramp for straight-in loading of cargo.

Construction of the prototype Model 107 started in 1957, and it flew in April 1958. It was designed for water landings, carrying 23 to 25 passengers in normal standard airline accommodations. The timing was fortuitous, as the military services in the late 1950's, foreseeing a buildup in Vietnam, began looking for replacements for their aging piston-powered CH-34 and CH-37 helicopters. The Marines opted for the smaller CH-46 version of the Vertol tandem-rotor design, while the Army chose the larger CH-47 version.

Both the CH-46 and the CH-47 helicopters became the workhorse, cargo-carrying helicopters of their respective services in Vietnam. They are equipped for external carriage as follows (refer back to Figure 14). The hook is mounted on rollers on a removable lateral beam in a rescue hatch in the cargo compartment floor. The hook assembly does not include a swivel and is not free to rotate with possible load rotation. There is adequate clearance in the well for the air crewman to observe the load and to gain access to the hook if necessary.

TABLE II

SUMMARY OF THE CHARACTERISTICS
OF PRINCIPAL ARMY AND MARINE HELICOPTERS
WITH EXTERNAL CARGO-CARRYING CAPABILITIES[1]
(1966 THROUGH 1972)

Helicopter	Principal User	Name	Mfr.	Procurement Cost ($)	Length of Fuselage	No. of Engines	HP - Each Engine	Max. Cruising Speed (mph)	Weights and Payload Capacity (lb) Empty	Max. T. O.	Design Payload	Max. Payload	Internal Troop Capacity	Hook	Comments on External Cargo-Carrying Capability
UH - 1D	Army	Iroquois (Huey)	Bell	237,000	41' - 10¼"	1	1,100		4,939	9,500	1,386[2]	3,650[2]	1 to 14	Eastern Rotorcraft 4000-lb Electromechanical	Blind to air crew hook inst. in belly of A/C. Hook not normally supplied after 1964. Very little used for external cargo in RVN.
UH - 1H	Army	Iroquois (Huey)	Bell	293,000	41' - 10¼"	1	1,400	127	4,973	9,500	1,750	4,650	1 to 14	Eastern Rotorcraft 4000-lb Electromechanical	
CH - 46A	Marines	Sea Knight	Boeing-Vertol		44' - 10"	2	1,250	159	12,406	21,400	2,800[3]	4,000	26	Aeroquip 10,000-lb Electromechanical	
CH - 46D	Marines	Sea Knight	Boeing-Vertol		44' - 10"	2	1,400	166	13,067	23,000	3,200[3]	4,550	26	Boeing Hydraulic/Pneumatic	Hook mounted on rollers on curved transverse beam pivoted in operating in belly of A/C. Air crewman has access both to observe load and to manually operate the hook. Loads always picked up with the A/C hovering.
CH - 46F	Marines	Sea Knight	Boeing-Vertol		44' - 10"	2							26		
CH - 47A	Army	Chinook	Boeing-Vertol	990,000	51' - 0"	2	2,200	127	17,932	33,000	10,618	15,068	33 to 44	Boeing Hydraulic/Pneumatic	
CH - 47B	Army	Chinook	Boeing-Vertol	1,063,000	51' - 0"	2	2,850	178	19,375	33,000	13,625	19,176	33 to 44	Boeing Hydraulic/Pneumatic	
CH - 47C	Army	Chinook	Boeing-Vertol	2,026,000	51' - 0"	2	3,750	189	20,251	33,000	12,760	19,760	33 to 44	Boeing Hydraulic/Pneumatic	
CH - 53A	Marines	Sea Stallion	Sikorsky		67' - 2"	2	2,850		22,444		10,000[3]	12,000	38	Eastern Rotorcraft 20,000-lb Electromechanical	
CH - 53D	Marines	Sea Stallion	Sikorsky		67' - 2"	2	3,925	173	23,485	42,000	12,500[3]	15,000	38	Eastern Rotorcraft 20,000-lb Electromechanical	
CH - 54A	Army	Skycrane	Sikorsky	2,134,500	70' - 3"	2	4,430	109	19,234	42,000	15,656	19,566	None	Eastern Rotorcraft 20,000-lb Electromechanical	Hook mounted on swivel attached to cable of 15,000-lb hoist[3]

1. Based on 10% fuel reserve and a 95°F temperature.
2. Air crewman operating the hook sits in a plastic pod to the rear of the pilots. He has complete visibility, ability to weigh the load, and even controls to fly the A/C. Loads are often, if not typically, lifted with the A/C landed. The landing gear is hydraulically extendible in order to lift the load, weigh it, and check the rigging prior to lift-off.
3. Estimated from load weights described in operational records and HP ratios to other models.

TABLE II

SUMMARY OF THE CHARACTERISTICS OF PRINCIPAL ARMY AND MARINE HELICOPTERS WITH EXTERNAL CARGO-CARRYING CAPABILITIES[1] (1966 THROUGH 1972)

Helicopter	Principal User	Name	Mfr.	Procurement Cost ($)	Length of Fuselage	No. of Engines	HP - Each Engine	Max. Cruising Speed (mph)	Weights and Payload Capacity (lb) Empty	Max. T. O.	Design Payload	Max. Payload	Internal Troop Capacity	Hoo
UH – ID	Army	Iroquois (Huey)	Bell	237,000	41' - 10¾'	1	1,100		4,939	9,500	1,366*	3,650*	1 to 14	Eastern Ro 4000-lb Electromec
UH – IH	Army	Iroquois (Huey)	Bell	293,000	41' - 10¾'	1	1,400	127	4,973	9,500	1,750	4,650	1 to 14	Eastern Ro 4000-lb Electromec
CH – 46A	Marines	Sea Knight	Boeing-Vertol		44' - 10"	2	1,250	159	12,406	21,400	2,800[3]	4,000	25	Aeroquip 1 Electromec
CH – 46D	Marines	Sea Knight	Boeing-Vertol		44' - 10"	2	1,400	166	13,067	23,000	3,200[3]	4,550	25	Boeing Hydraulic/F
CH – 46F	Marines	Sea Knight	Boeing-Vertol		44' - 10"	2							25	
CH – 47A	Army	Chinook	Boeing-Vertol	990,000	51' - 0"	2	2,200	127	17,932	33,000	10,618	15,068	33 to 44	Boeing Hydraulic/F
CH – 47B	Army	Chinook	Boeing-Vertol	1,063,000	51' - 0"	2	2,850	178	19,375	33,000	13,625	19,175	33 to 44	Boeing Hydraulic/F
CH – 47C	Army	Chinook	Boeing-Vertol	2,026,000	51' - 0"	2	3,750	189	20,251	33,000	12,760	19,760	33 to 44	Boeing Hydraulic/F
CH – 53A	Marines	Sea Stallion	Sikorsky		67' - 2"	2	2,850		22,444		10,000[3]	12,000	38	Eastern Ro 20,000-lb Electromec
CH – 53D	Marines	Sea Stallion	Sikorsky		67' - 2"	2	3,925	173	23,485	42,000	12,500[3]	15,000	38	Eastern Ro 20,000-lb Electromec
CH – 54A	Army	Skycrane	Sikorsky	2,134,000	70' - 3"	2	4,430	109	19,234	42,000	15,556	19,556	None	Eastern Ro 20,000-lb Electromec

1. Based on 10% fuel reserve and a 95°F temperature.
2. Air crewman operating the hook sits in a plastic pod to the rear of the pilots. He has complete visibility, ability to weigh the load, and even controls to fly the A/C. Loads are often, if not typically, lifted with the A/C landed. The landing gear is hydraulically ex'endible in order to lift the load, weigh it, and check the rigging prior to lift-off.
3. Estimated from load weights described in operational records and HP ratios to other models.

TABLE II

SUMMARY OF THE CHARACTERISTICS
OF PRINCIPAL ARMY AND MARINE HELICOPTERS
WITH EXTERNAL CARGO-CARRYING CAPABILITIES[1]
(1966 THROUGH 1972)

...nt	Length of Fuselage	No. of Engines	HP - Each Engine	Max. Cruising Speed (mph)	Weights and Payload Capacity (lb) Empty	Max. T. O.	Design Payload	Max. Payload	Internal Troop Capacity	Hook	Comments on External Cargo-Carrying Capability
)	41' - 10¾'	1	1,100		4,939	9,500	1,366*	3,650*	1 to 14	Eastern Rotorcraft 4000-lb Electromechanical	Blind to air crew hook inst. in belly of A/C. Hook not normally supplied after 1964. Very little used for external cargo in RVN.
)	41' - 10¾'	1	1,400	127	4,973	9,500	1,750	4,650	1 to 14	Eastern Rotorcraft 4000-lb Electromechanical	
	44' - 10"	2	1,250	159	12,406	21,400	2,800[3]	4,000	25	Aeroquip 10,000-lb Electromechanical	
	44' - 10"	2	1,400	166	13,067	23,000	3,200[3]	4,550	25	Boeing Hydraulic/Pneumatic	Hook mounted on rollers on curved transverse beam pivoted in operating in belly of A/C. Air crewman has access both to observe load and to manually operate the hook. Loads always picked up with the A/C hovering.
	44' - 10"	2							25		
)	51' - 0"	2	2,200	127	17,932	33,000	10,618	15,068	33 to 44	Boeing Hydraulic/Pneumatic	
)	51' - 0"	2	2,850	178	19,375	33,000	13,625	19,175	33 to 44	Boeing Hydraulic/Pneumatic	
)	51' - 0"	2	3,750	189	20,251	33,000	12,760	19,760	33 to 44	Boeing Hydraulic/Pneumatic	
	67' - 2"	2	2,850		22,444		10,000[3]	12,000	38	Eastern Rotorcraft 20,000-lb Electromechanical	
	67' - 2"	2	3,925	173	23,485	42,000	12,500[3]	15,000	38	Eastern Rotorcraft 20,000-lb Electromechanical	
)	70' - 3"	2	4,430	109	19,234	42,000	15,556	19,556	None	Eastern Rotorcraft 20,000-lb Electromechanical	Hook mounted on swivel attached to cable of 15,000-lb hoist[2]

ar of the pilots. He has complete visibility, ability to weigh the load, and even controls to fly the A/C. Loads are often, if not typically,
xtendible in order to lift the load, weigh it, and check the rigging prior to lift-off.
and HP ratios to other models.

While early models employed Aeroquip or Eastern Rotocraft electromechanical designs, in later models a hydraulic-pneumatic actuated Boeing-Vertol designed hook was used. Normal remote activation is hydraulic by means of electrically controlled solenoid valves. It is slower in operation than competitive electromechanical hooks in other helicopters, requiring about 3 seconds to open vs. milliseconds for the electromechanical hook. However, it does not require the relatively delicate latching mechanisms that are basic to electromechanical hooks.

The hydraulic actuation cylinder is backstopped by a pneumatic cylinder. Rapid release of air from this pneumatic cylinder constitutes the emergency release and literally blows the hook open. The pneumatic cylinder has to be charged to about 2500 psi with equipment external to the helicopter. One charge is adequate for 1 to 3 emergency releases. There is a built-in pressure gauge which air crewmen are instructed to check routinely, since too little pressure can cause the hook to open inadvertently.

Normal hook release is effected by a fully exposed switch mounted on the pilot's collective control grip and the air crewman's pistol grip pendant control. The switches are activated by moving the little finger down a very small distance from its normal grip position.

Emergency release is effected by pulling a D-ring on the hook itself or by the pilot actuating the same mechanism via a floor pedal in the cockpit. This floor pedal is mechanically coupled to the hook by a cable. The adjustment of this cable is critical, since the hook can be actuated by the combination of a short cable (as the result of incorrect installation) and traverse motion of the hook in flight.

Both the pilots and air crewmen have arming master switches. The pistol grip control of the air crewmen functions only if both master switches are armed. The pilots' functions only when their master switch is armed. The pilots also have a "hook-open" indicator light.

The pilots of these helicopters cannot observe the load. They have to be "talked over" the load and drop point by the air crewmen. Ground crew guidance, while part of standard operating procedures, is largely ignored by the pilots, because they have found the practice unreliable. The pilots are also substantially unaware of the load's in-flight profile, except as they are informed by the air crewmen. Some early models were fitted with rear and under-view mirrors under the pilots' feet, but these were removed in conflict zones because they reflected light that pinpointed the position of the helicopter. No other instruments that would give the pilots a sense of external load position, weight, or flight dynamics were included in the helicopter's design.

2. The CH-54 Helicopter

The CH-54 helicopter was designed initially in the early 1960's for universal heavy-lift military transport duties. The CH-54 has a 15,000-lb-capacity removeable winch with 150 feet of cable for single-point external cargo handling. The hook is attached to the cable with a swivel which prevents the slings from winding up and generating high stresses when the load spins aerodynamically. The swivel is unique to integral external load-carrying cargo helicopter equipment to date. The helicopter is also equipped with interchangeable pods suspended from four independent winches. Thus equipped, it is suitable for troop transport, containerized cargo, or field hospital operations. However, evidence indicates that the pods or winches were seldom utilized for other multipoint suspensions in the Vietnam conflict – the former, because of the relative slowness of rigging pods on the ground, and the latter, because of the pilot's perception of additional hazards associated with multipoint suspensions.

The CH-54 is a somewhat larger and more greatly powered helicopter than the CH-47, having a 71-foot-long fuselage vs. 51 feet for the CH-47, and 8860 hp vs 7500 hp in the CH-47. However, it does not exceed the payload capacity of the CH-47 as much as its dimensions and power might suggest, as shown below:

	Design Payload (lb)	Maximum Payload (lb)
CH-47C	12,760	19,760
CH-54A	15,556	19,556

The emphasis on the original Army procurement of the CH-54 was to investigate the heavy-lift concept, and this aircraft continues to be looked upon and utilized as the heavy-lift helicopter in the Army arsenal. The CH-54 is exclusively an external cargo-carrying helicopter; it does not have an internal cargo space. For this reason it is equipped in somewhat more sophisticated ways for its single-purpose external carriage function than the multipurpose CH-46's, CH-47's, and CH-53's.

In the CH-54 (refer to Figure 15) the air crewman sits in a compartment behind the pilot with full visibility of the load. He has duplicate pilot controls and can fly the aircraft from his own position rather than having to direct the pilot over the load as is done in other helicopters. Both the air crewman and the pilot have load weight-measuring instruments. The weight of the load can be precisely measured after takeoff to assess, for instance, the aircraft's capability

of flying to higher altitudes. Moreover, load instability can, to a degree, be continously monitored by the pilot using this instrument during the flight. The normal hook-release switch is exposed on the collective control grip – as in the CH-47 – but it is operated transversely by the thumb on the right side. This requires crossing the thumb across the control, calling for a very conscious effort that is unlikely to be done inadvertently.

The hook is electromechanical in principle. The winch is hydraulically driven and mounted with a mechanism to provide load isolation (dampening). Just below the hook the cable runs through an explosively actuated guillotine which serves as an emergency release. Later models have two redundant guillotines. The emergency release, of course, actuates the guillotine, which severs the cable and drops the hook and the swivel along with the load, necessitating a significant amount of repair. For this reason, every emergency release atypically costs probably several thousands of dollars more than the value of the damage to the rigging and load dropped.

The arming switch and indicator light setup and emergency release controls of the CH-54 are generally quite similar to those of the CH-47.

3. The CH-53 Helicopter

In August 1962 the Navy contracted with Sikorsky to produce a heavy assault transport helicopter (the CH-53) for use by the Marine Corps. The helicopter, subsequently delivered in 1966, used many of the components of the CH-54. It is configured and looks somewhat like a CH-54, having an integral cargo cabin in lieu of the CH-54's cutaway external cargo space. It is dissimilar to the CH-54, however, in that it has fuel tanks on the end of sponsons. It is also faster (173 vs. 109 mph) and more maneuverable than the CH-54. It has retractable landing gear and in flight is much more streamlined than the CH-54. It is intended to operate under all weather and climatic conditions.

Its cargo space is similar to the CH-46's and CH-47's in that it has a rear-loading cargo ramp. Its internal cargo volume is comparable to that of the CH-47. Its external cargo carriage is also similar to that of CH-46 and CH-47 helicopters. The cargo hook is located in a bulkhead opening in the cargo space floor. Pilot visibility and means of communication with the air crew are also probably similar to those of the Boeing-Vertol helicopter. We have not had the opportunity to examine this helicopter in detail, but Sikorsky tells us that the normal electrical hook-release control functions are similar, if not identical, to those of the CH-54. The emergency release is a manually activated T-handle.

The maximum payload capacity of the CH-53 is about 15,000 pounds, or about 23% less than the CH-54A or CH-47C. However, this capacity is almost four times the 4100-pound maximum capacity of the Marine CH-46F. Thus, the Marines fly cargo helicopters with a load capability range of about 4 to 1, while the Army cargo helicopter range of the CH-47A (15,068 pounds) to the CH-54A (19,556 pounds) varied by only 23%.

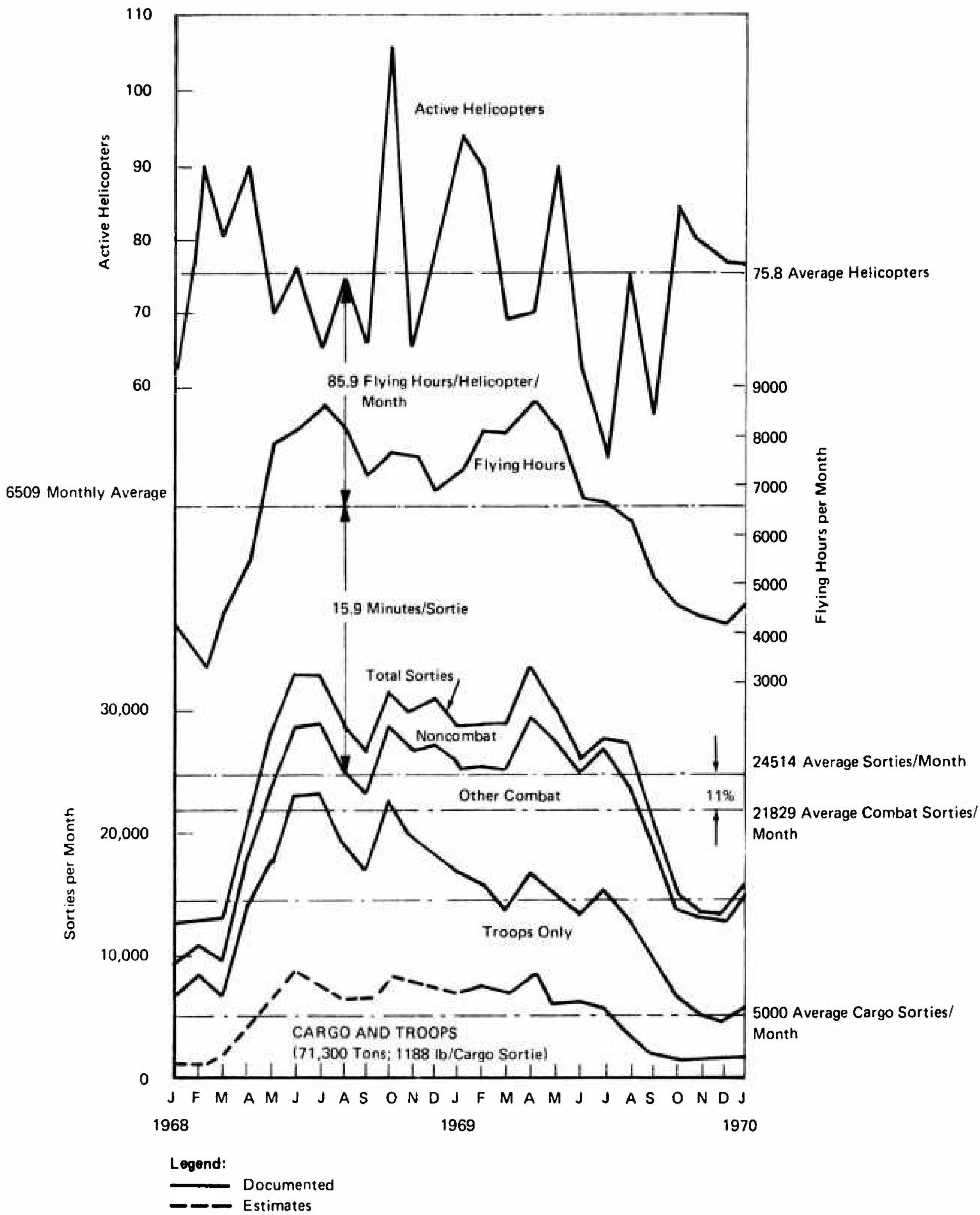
C. OVERALL UTILIZATION OF CARGO HELICOPTERS IN VIETNAM DURING 1968 AND 1969

We have previously discussed our reason for focusing on active helicopters in the 1968 and 1969 period. Figures 20, 21, 22, and 23 present a rather complete picture of how the four types of helicopters of principal interest were utilized by the Army and Marines in Vietnam during this period. Ultimately we will be primarily interested in the breakdown of sorties flown and their characteristics. Companies, aviators, combat-ready aircraft, and the like, are part of the organizational maintenance problems which add perspective to our understanding, but are not of primary importance.

The Army's CH-47 companies had a TOE allocation of 16 helicopters maximum and 33 aviators. There were 21 such companies in Vietnam at the end of 1969. These companies actually had about 14 active helicopters on the average. The consensus of the pilots was that only about 7.7 helicopters would be combat-ready at any given time. A slightly smaller number, perhaps 6, would be flown each day. The average CH-47 company flew about 2400 sorties a month, requiring about 19.3 minutes for each sortie performed. The average CH-47 pilot flew slightly over 50 hours a month.

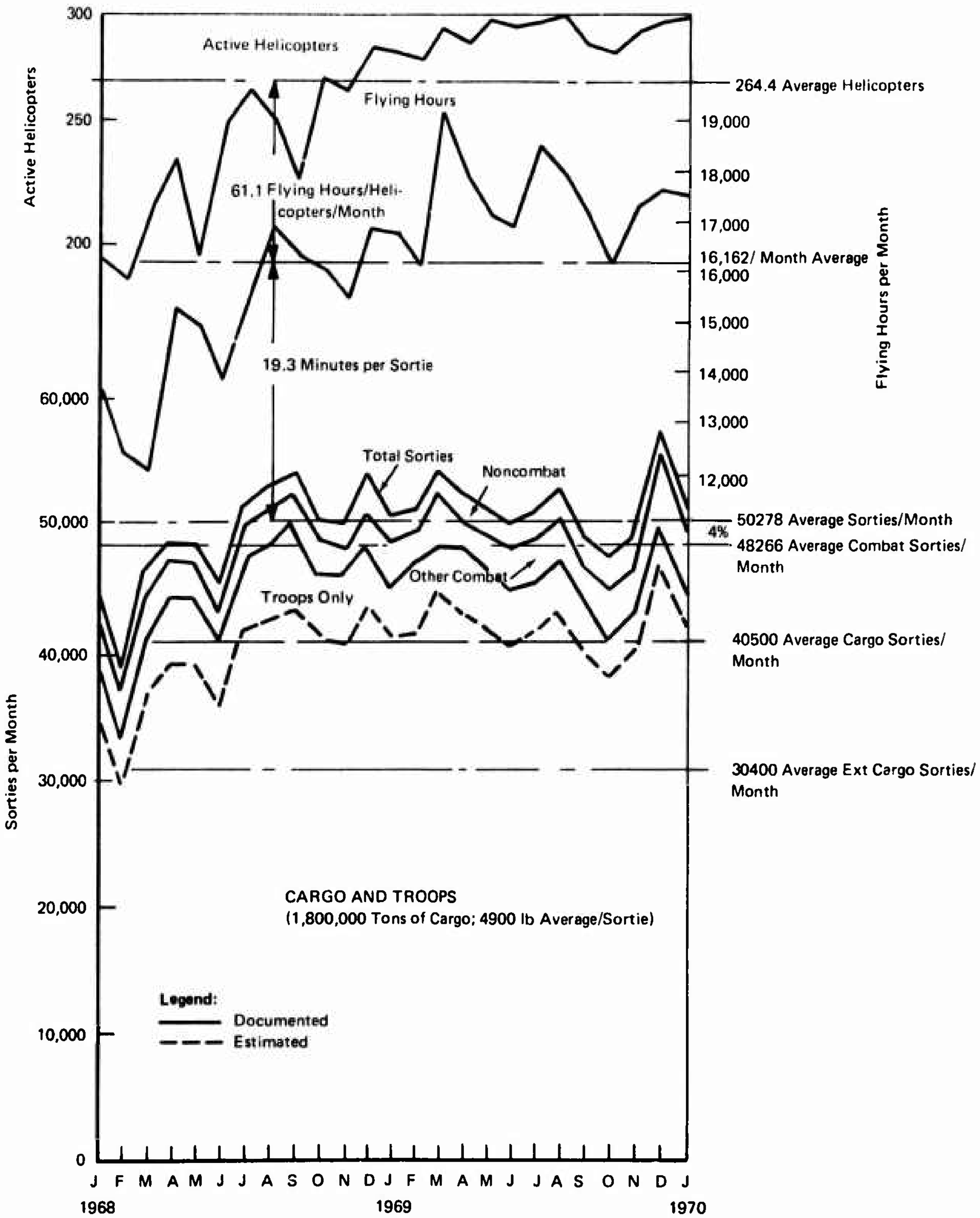
The Army's CH-54 companies had a TOE allocation of nine helicopters maximum, and there were three such companies in Vietnam at the end of 1969. The average CH-54 company flew about 1000 sorties a month, and the sorties were much slower than the CH-47's, requiring about 28 minutes per sortie.

The Marine equivalent of a helicopter company is a squadron. Two types of squadrons are applicable: a medium squadron (HMM), which was allocated a maximum of 24 CH-46's and 53 aviators, and a heavy squadron (HMH), which was allocated 18 CH-53's maximum and 45 aviators. It had been estimated that there were seven land-based and two shipboard-based CH-46 squadrons during this period. If this were true, they must have had far fewer than their full-strength allocation, or 8.5 helicopters per squadron. The CH-46 is the smallest of the four helicopters under consideration, and it performed sorties the fastest (15.9 minutes) and at a much greater rate than any of the other three helicopter types. The average CH-46 performed 288 sorties per month in the period as compared to 183 for the CH-47, 88.8 for the CH-54, and 135 for the CH-53. This helicopter



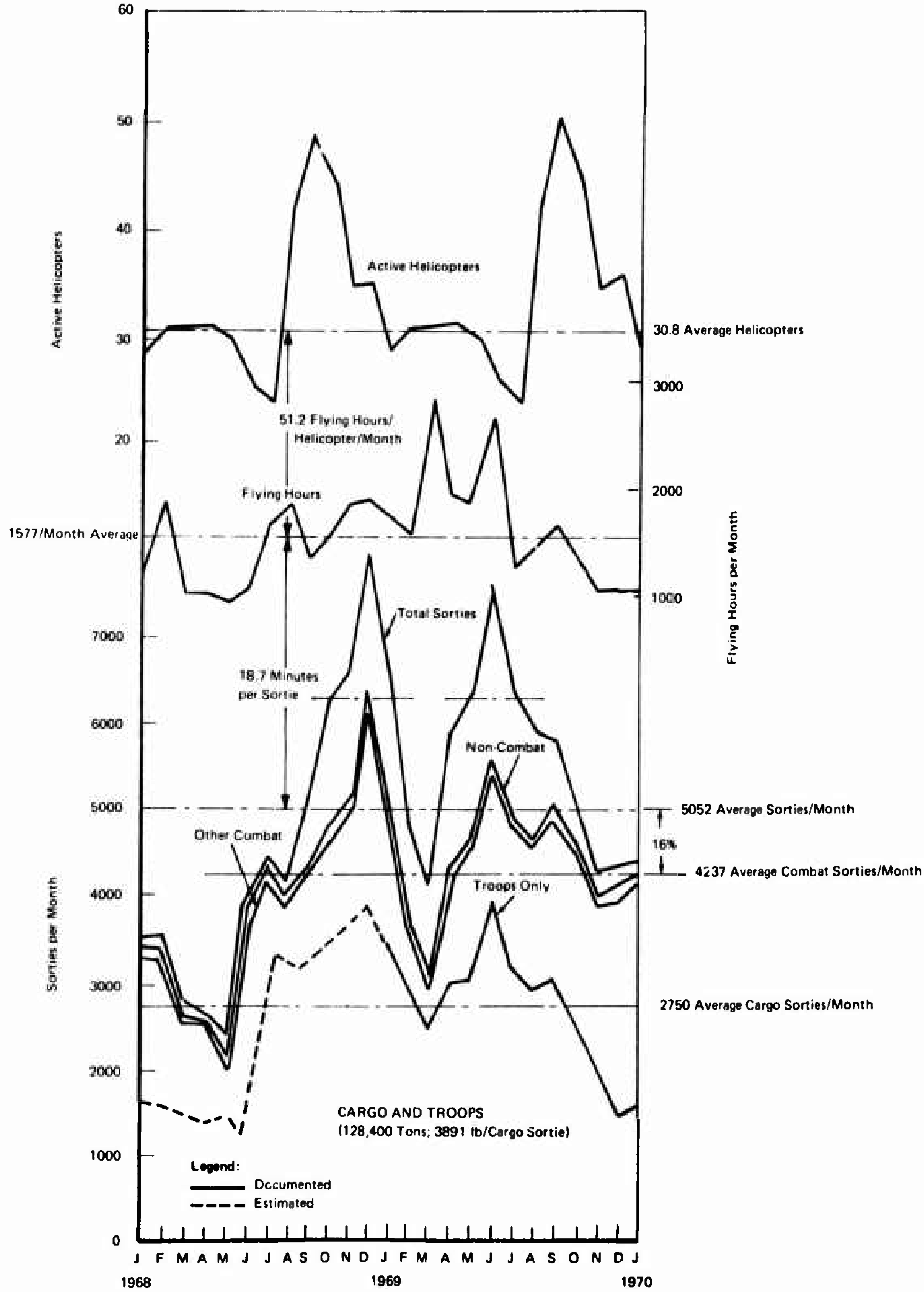
Source: Marine Corps Operational Analysis Groups Analysis of JCS OPREA File Data.

FIGURE 20. NUMBERS AND UTILIZATION OF ACTIVE MARINE CH-46 HELICOPTERS IN VIETNAM (1968 and 1969).



Sources: Marine Corps Operational Analysis Group's Analysis of JCS OPREA File Data
Boeing-Vertol Data
Arthur D. Little, Inc., estimates

FIGURE 21. NUMBERS AND UTILIZATION OF ACTIVE ARMY CH-47 HELICOPTERS IN VIETNAM (1968 and 1969).



Source: Marine Corps Operation Analysis Group's Analysis of JCS OPREA File Data

FIGURE 22. NUMBERS AND UTILIZATION OF ACTIVE MARINE CH-53 HELICOPTERS IN VIETNAM (1968 and 1969).

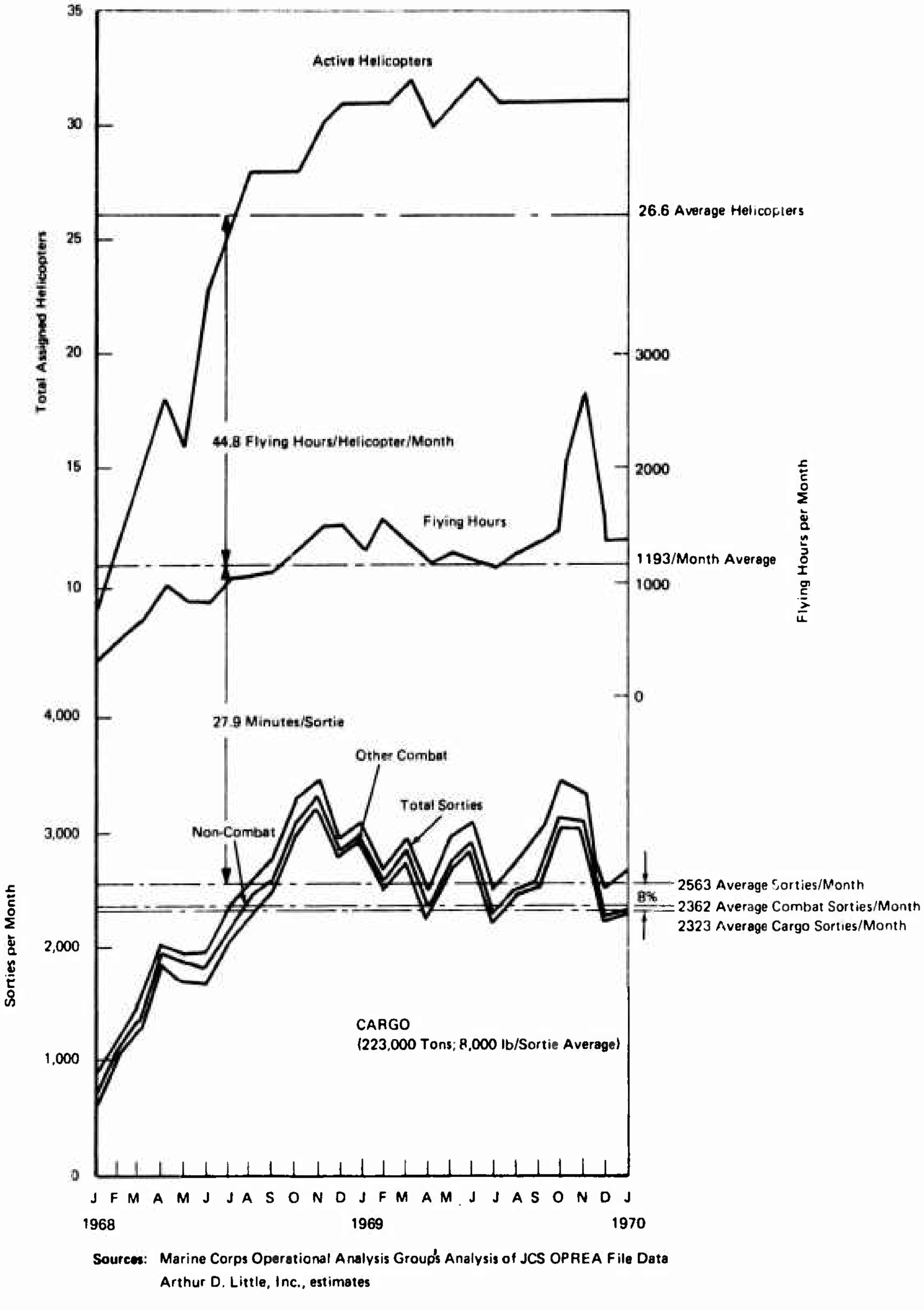


FIGURE 23. NUMBERS AND UTILIZATION OF ACTIVE ARMY CH-54 HELICOPTERS IN VIETNAM (1968 and 1969).

was obviously used intensively and, one would suspect, quite differently than the other three helicopters.

It also has been estimated that there were three HMH CH-53 squadrons all land-based in Vietnam during 1965-69. This would mean that these squadrons had far fewer than their full-strength allocation, or 10 helicopters per squadron. The evidence is that the utilization of the CH-53 was quite similar to that of the CH-47.

Returning to Figures 20 through 23, we are generally interested in the total sorties and specifically interested in the cargo sorties flown. It will be observed that the CH-54 is atypical of the group, in that – not having integral internal cargo space -- a very high percentage of all sorties flown were cargo sorties. No troop and very few other combat sorties were flown; moreover, all cargo sorties were external carriage.

For the other cargo helicopters, sorties involved both cargo, troop, and other combat missions. Frequently, if not typically, cargo and troops were mixed in a single sortie. Other combat involved their use as a gunship for observation or other combat-associated sorties.

The noncombat sorties for all the helicopters were, as far as we know, principally maintenance checks. Some correlation can be observed in the figures between the attenuation in numbers of aircraft and the magnitude of noncombat sorties.

We were specifically interested in external-cargo sorties. The CH-54 was no problem – all sorties were external carriage. Boeing-Vertol's field representatives analyzed the experience of 12 CH-47 companies for 3 months in 1968. They found that 75% of all the cargo carried was external carriage. We assumed, therefore, that 75% was a valid figure for the CH-47 in both 1968 and 1969.

The Marines appear to have had a different experience. Conversations with Marine pilots with experience in Vietnam disclosed that they carried practically no external cargo in Vietnam in 1966. This makes sense because the CH-53's had not arrived in Vietnam at that time; the CH-34's had low payload capabilities and unreliable hooks, and the CH-46 was just being phased in at that time. Subsequently, they obviously developed both the helicopters and an appreciation for the technique. Examination of CH-53 operation logs from Vietnam suggested that an extremely high percentage of external carriage was utilized by 1968-69. Examination of comparable CH-46 logs was indecisive, but suggested that there was less emphasis on external carriage than shown by the Army. Marine pilots tended to feel, in general, that the Marine Corps carried less cargo externally than the Army.

Table III summarizes the performance of the four helicopters in Vietnam during the period of interest. It is imperative that the reader grasp the differences in the ways the various helicopters were utilized. Only then can he fully differentiate the external cargo-handling failure experiences and their presumptive causes.

D. LOAD CATEGORIES AND RIGGING MATERIALS UTILIZED

1. Load Categories

We were interested in the categories of external loads carried and the distribution of the categories among loads that were typically carried by the various helicopters. Different load categories tend to have different aerodynamic characteristics, failure rates, and replacement values if they are lost. Since failure reports give only the number of failures, one can arrive at failure rates only by determining the frequency rate at which this particular load was carried.

Figure 24 shows the six categories into which we have chosen to separate loads. We believe that the categories are fairly specific. However, there is some overlap between palletized and net loads. The Army often carries palletized loads in nets. For this reason there may be some confusion on net or palletized loads reported by them. A strictly palletized load is much more frequently utilized by the Marines than by the Army. Conversely, net loads are less frequently utilized by the Marines than by the Army. The other types of loads are fairly self-explanatory.

Unfortunately, none of the military services kept records that would permit an accurate tabulation of load distribution. For this reason our principal source of data on the subject is the consensus of pilots and air crewmen interviewed. It was possible to check their estimates by also summarizing their estimates of failures in the various load categories. The most comprehensive information we were able to develop on the subject was compiled on the CH-47 helicopter. This is fortunate because this helicopter carried on the order of 81% of the total tonnage transported by helicopters in Vietnam. We have less precise but usable load distribution information on the CH-54, but little to none for the Marine CH-46 and CH-53 helicopters. What little information we have on these two helicopters suggests that the CH-46 carried, relative to its capabilities, more troops and less cargo than the comparable ratios for the CH-47. The CH-53 appears to have been used in ways comparable to the CH-47.

Table IV gives the estimated load distribution for the two Army helicopters.

TABLE III

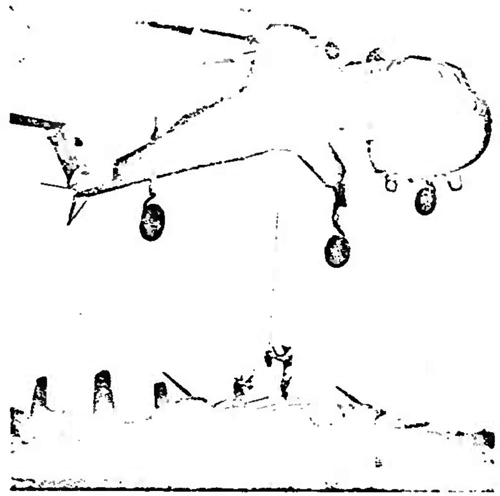
SUMMARY OF THE NUMBERS AND UTILIZATION OF PRINCIPAL ARMY AND MARINE CORPS CARGO HELICOPTERS IN VIETNAM (1968 and 1969)

Line	Parameter	Army		Marine Corps		
		CH-47	CH-54	CH-46	CH-53	Totals
1	Peak No. of active helos.	301	32	107	51	491
Averages						
2	Number of active helos.	264.4	26.6	75.8	30.8	397.6
3	Total sorties/helo/mo.	190	88.8	288	138	–
4	Cargo sorties/helo/mo.	153	87	66	89	88.4
5	Noncombat sorties/helo/mo. (%)	4	8	11	16	–
6	Flying time/helo/mo. (hr)	61.1	44.8	85.9	51.2	–
7	Flying time/sortie (min)	19.3	27.9	15.9	18.7	–
8	Avg. Load/cargo sortie (lb)	4900	8000	1200	3900	–
9	Max. payload utilization (%)	27	41	31	25	–
Totals						
10	Cargo tonnage carried/mo. by this type helo	150	18.6	5.9	10.7	185.2
11	Percent of total cargo tonnage (10^6 lb) carried by all four helos.	81	10	3	6	100
12	Percent of total cargo tonnage by services	91		9		100

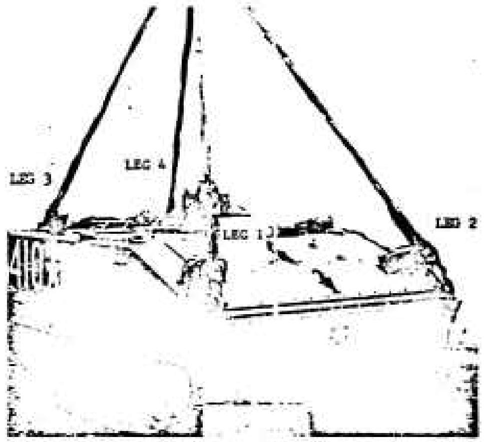
TABLE IV

ESTIMATED LOAD DISTRIBUTION OF ARMY CARGO HELICOPTERS IN VIETNAM (1968 TO 1969)

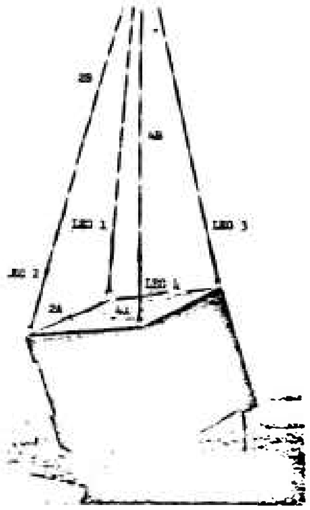
No.	Load Category	Helicopter CH-47	Helicopter CH-54
1.	Disabled aircraft	7.3	2.9
2.	Other single unsupported items	28.8	69.8
3.	Containerized loads	11.7	4.7
4.	Palletized loads	14.1	4.9
5.	Loads in nets	32.7	13.4
6.	Chained or strapped-together loads	5.8	4.2
		100.4%	99.9%



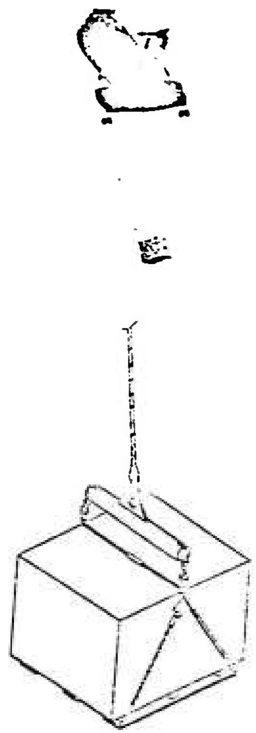
1. Aircraft Recoveries



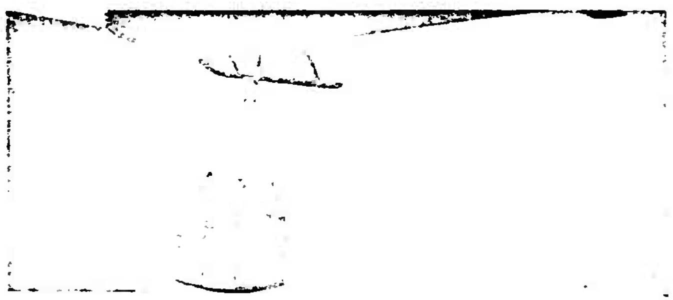
2. Single Unsupported



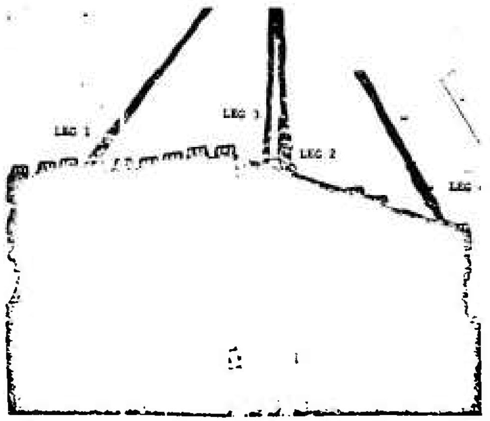
3. Containerized



4. Palletized



5. Loads in Nets

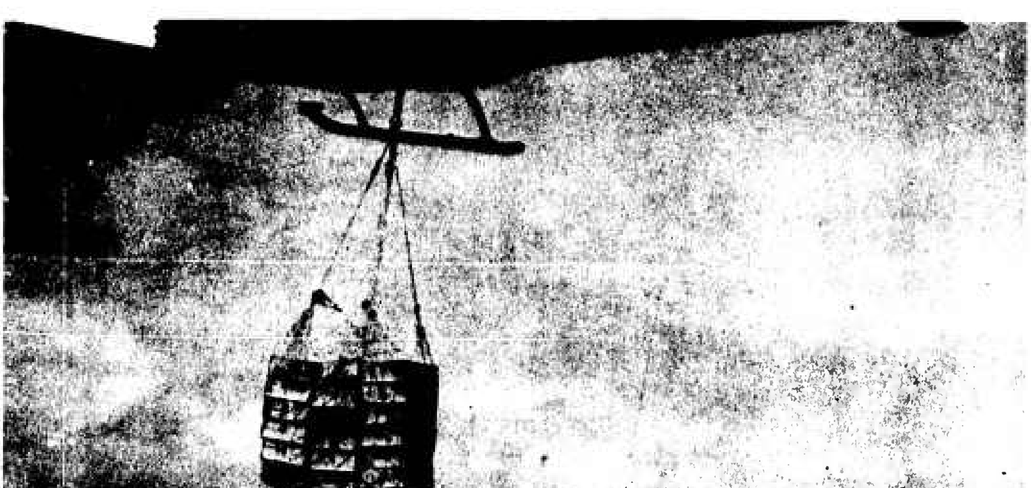


6. Chained/Strapped Together

FIGURE 24. HELICOPTER EXTERNAL LOAD CATEGORIES.

1. Aircraft Recoveries

2. Single Unsupported

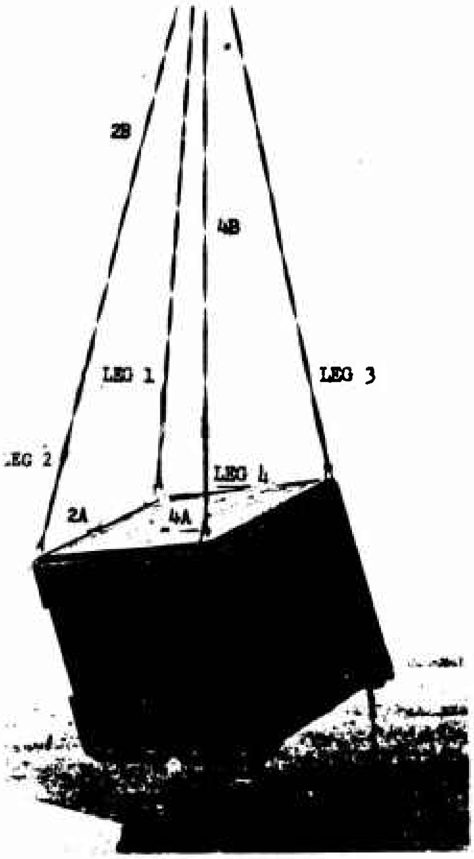


5. Loads in Nets

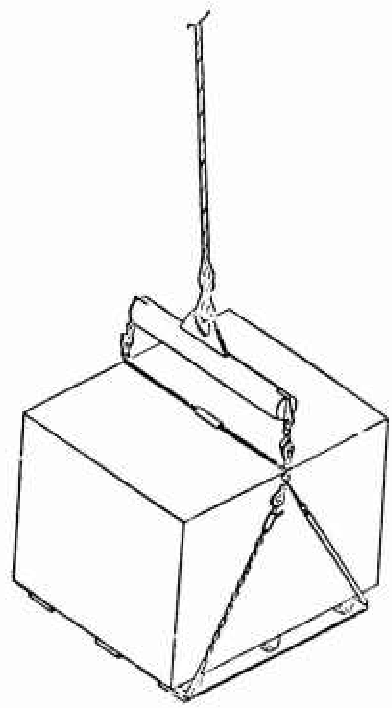
6. Chai

FIGURE 24. HELICOPTER EXTERNAL LOAD CATEGORIES.

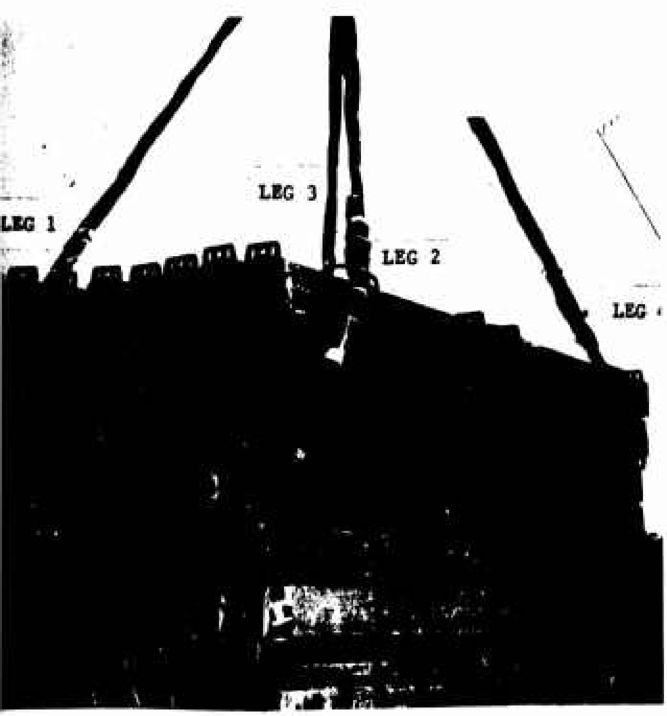
Unsupported



3. Containerized



4. Palletized



6. Chained/Strapped Together

2. Rigging Materials Utilized

Finally, we were interested in the specific materials employed in rigging external loads. The names of the various items and their points of application in the system are called out in Figures 14 and 15. Some of the materials necessary are listed in the Federal Stock Catalogs. These items are shown in Table V. The Federal Stock Catalogs are a series of pictorially illustrated books that make it, if not easy, at least possible for the uninitiated ground crewman to find a rigging item he wants at a depot. The problem is that, while the depot probably has the item on hand, many of the most current items are not listed in the Federal Stock Catalogs. The procedure for getting an item listed often requires years. Many items change so frequently that they never become listed or are actually obsolete when listed.

For those items not listed, the ground crewman would have to know specifically what he wanted and probably even have an inventory number. The only way he could have procured this information would have been from a manual or other communication document. Little-used but often critical items, such as drogue chutes and belly bands, can present particularly difficult procurement problems for the ground crewman.

E. SUMMARY OF THE CAUSES OF SPECIFIC FAILURES EXPERIENCED

Tables VI through IX present summaries of external cargo failures in the CH-46, CH-47, CH-53, and CH-54 helicopters, respectively, and Table X presents a distributed average of the 371 external cargo failures in the same four helicopters. The failures of the Marine Corps CH-46 and CH-53 helicopters were taken totally from documented records at the U.S. Naval Safety Center in Norfolk, Virginia. The Army CH-47 and CH-54 failure reports were principally based on recitations of specific failures experienced by pilots and air crewmen. However, a significant number of documented failure records involving the CH-47 were found and incorporated.

The predominant experience – with the possible exception of that of the CH-46 – is based on activities in Vietnam and was predominantly recorded in 1968, 1969, and 1970, the years of paramount interest to the study.

F. CONSENSUS OF CAUSES OF FAILURES

During the course of our study, we solicited consensus data on causes of failures from pilots and air crewmen with experience in Vietnam, using the questionnaire shown in Chapter III. In all cases we personally supervised its compilation. Data were obtained from 33 persons experienced with the CH-47

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TABLE V

FEDERAL STOCK CATALOG-RECOMMENDED MATERIALS FOR EXTERNAL CARGO-HANDLING AND THEIR CAPACITIES

FSN	Nomenclature	Rated Strength (lb)	*Rated Strength When Used as a Leg of a Sling at the Following Angles (lb) 30°	35°	40°	45°
1670-090-5354	Clevis, Suspension, Large	40,000	–	–	–	–
1670-242-9169	Bag, Cargo, A/C A-22	2,200	–	–	–	–
1670-242-9173	Bag, Cargo, A/D A-21	500	–	–	–	–
1670-251-1153	Sling, Cargo, A/D A-7A	500	–	–	–	–
1670-360-0300	Clevis, Cargo Platform	15,000	–	–	–	–
1670-360-0304	Clevis, Suspension, Small	20,000	–	–	–	–
1670-360-0308	Clevis, Suspension, Medium	20,000	–	–	–	–
1670-360-0466	Ring, D, Prcht Harness (MIL-H-7195)	5,000	–	–	–	–
1670-360-0540	Strap, Tiedown, A/D, 15 Ft	5,000	4,330	4,100	3,830	3,535
1670-753-3788	Sling, Cargo, A/D, 3 Ft, 3 Loop	20,000	17,330	16,390	15,330	14,140
1670-753-3789	Sling, Cargo, A/D, 8 Ft, 2 Loop	13,500	11,700	11,065	10,345	9,550
1670-753-3790	Sling, Cargo, A/D, 9 Ft, 2 Loop	13,500	11,700	11,065	10,345	9,550
1670-753-3791	Sling, Cargo, A/D, 11 Ft, 2 Loop	13,500	11,700	11,065	10,345	9,550
1670-753-3792	Sling, Cargo, A/D, 12 Ft, 2 Loop	13,500	11,700	11,065	10,345	9,550
1670-753-3793	Sling, Cargo, A/D, 16 Ft, 2 Loop	13,500	11,700	11,065	10,345	9,550
3940-641-3409	Sling, Cargo Net, Nylon Rope 8 x 8	–	–	–	–	–
3940-641-3410	Sling, Cargo Net, Nylon Rope 10 x 10	–	–	–	–	–
3940-656-7998	Sling Set, Cargo, Universal	7,500	–	–	–	–
NOTE: THE ABOVE SET IS COMPOSED OF FSN 3940-675-5001, -5002, -5003						
3940-675-5001	Sling, Endless, 10" Dia.	7,500	–	–	–	–
3940-675-5002	Sling, Endless, 4' Long	2,500	2,170	2,050	1,915	1,770
3940-675-5003	Sling, Endless, 8' Long	2,500	2,170	2,050	1,915	1,770
3940-744-8507	Sling, Cargo Net, Steel Wire Rope	5,000	–	–	–	–
3940-892-4375	Sling, Cargo Net, Nylon 12 x 12	–	–	–	–	–
3940-137-0077	(Cannot be Identified)	–	–	–	–	–
3030-185-0490	Shackle, Anchor, Screw Pin	10,850	–	–	–	–
8465-889-3771	(Cannot be Identified)	–	–	–	–	–
1670-799-8596	Load Coupler, 8 Spool	–	–	–	–	–
1670-799-8597	Load Coupler, 12 Spool	–	–	–	–	–
1670-823-5040	Sling, Cargo, A/D 11 Ft, 3 Loop	20,000	17,330	16,390	15,330	14,140
1670-823-5041	Sling, Cargo, A/D 12 Ft, 3 Loop	20,000	17,330	16,390	15,330	14,140
1670-823-5042	Sling, Cargo, A/D 16 Ft, 3 Loop	20,000	17,330	16,390	15,330	14,140
1670-823-5043	Sling, Cargo, A/D 20 Ft, 3 Loop	20,000	17,330	16,390	15,330	14,140
1670-902-3080	Sling, Cargo, Multiple Leg (Chain Leg)	40,000	34,660	32,790	30,600	28,290
3940-298-2978	(Cannot be Identified)	–	–	–	–	–
3940-298-3985	Sling, Cargo, Paulin, 12' x 12'	2,700	–	–	–	–
3940-542-4898	Sling, Cargo, Net, Manila Rope, 14' x 14'	1,300	–	–	–	–
3940-606-9960	(Cannot be Identified)	–	–	–	–	–
3940-606-9961	Sling, Multi Leg	–	–	–	–	–

*Leg strength = rated strength x the cosine of the indicated sling angle

TABLE VI

SUMMARY OF 100 MARINE/NAVY CH-46 EXTERNAL CARGO FAILURES

Vietnam	54%
Other Locations	46%
Documented Failure Reports	100%
Recitations of Personal Experience	0%
Other	0%

	Percentage of All Failures																
		By Task Progression			By Load Density			By Load Stabilization		By Environment		By Load Types					
Causes of Failure	Total	Picking Up	Cruising – In-Flight	Delivering	Class I High Density	Class II Medium Density	Class III Low Density	Problems Encountered	No Problems Encountered	Adverse	Not Adverse	Aircraft Recoveries	Single Unsupported	Containers	Pallets	Nets	Strapped
Aircraft Subsystem																	
• Hook Load Release & Controls	26	7	13	4				1	25	1	25						
• Winch	NA	NA	NA	NA				NA	NA	NA	NA						
• Pendants	5	0	5	0				0	5	0	5						
Total	31	7	18	4				1	30	1	30						
Rigging																	
• Slings	31	2	11	0				0	13	0	13						
• Straps	3	2	1	0				0	3	0	3						
• Doughnuts	1	0	1	0				0	1	0	1						
• Clevises	1	0	1	0				0	1	0	1						
• Other Mechanical	0	0	0	0				0	0	0	0						
Total	18	4	14	0				0	18	0	18						
Load Containers & Attachments																	
• Nets	0	0	0	0		Insufficient Data		0	0	0	0			Insufficient Data			
• Other Mechanical	3	1	2	0				0	3	0	3						
Total	3	1	2	0				0	3	0	3						
Human Error																	
• Pilots	26	9	7	11				7	19	9	17						
• Pilot/Air Crew	19	5	0	14				0	19	14	5						
• Air Crew	0	0	0	0				0	0	0	0						
• Ground Crew	5	2	3	0				0	5	0	5						
Total	50	16	10	25				7	43	23	27						
Total Percent	102	28	45	29	3	57	40	8	94	24	78						
			102			100		102		102							

TABLE VII

SUMMARY OF 100 ARMY CH-47 EXTERNAL CARGO FAILURES

Vietnam	95%
Other Locations	5%
Documented Failure Reports	44%
Recitations of Personal Experience	52%
Other	4%

	Percentage of All Failures																				
		By Task Progression			By Load Density			By Load Stabilization		By Environment		By Load Types						By Rigging Configuration			
Causes of Failure	Total	Picking Up	Cruising – In-Flight	Delivering	Class I High Density	Class II Medium Density	Class III Low Density	Problems Encountered	No Problems Encountered	Adverse	Not Adverse	Aircraft Recoveries	Single Unsupported	Containers	Pallets	Nets	Strapped	Single-Legged	Two-Legged	Three-Legged	Four-Legged
Aircraft Subsystem																					
• Hook Load Release & Controls	9	0	3	5	1	5	1	0	9	1	8	1	5	1	0	1	0	0	3	2	5
• Winch	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
• Pendants	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Subtotal	9	0	3	5	1	5	1	0	9	1	8	1	5	1	0	1	0	0	3	2	5
Rigging																					
• Slings	28	6	24	0	6	18	1	1	27	1	27	1	10	0	0	6	6	5	2	7	10
• Straps	12	3	9	0	2	5	5	2	10	0	12	5	0	0	0	0	8	5	3	0	2
• Doughnuts	8	0	9	0	1	5	2	1	7	1	7	1	1	1	0	2	2	0	0	0	8
• Clevises	1	0	1	0	1	0	0	0	1	0	1	0	0	0	0	1	0	2	0	0	0
• Other Mechanical	1	0	1	0	0	0	1	0	1	0	1	1	0	0	0	0	0	2	0	0	0
Subtotal	50	9	44	0	10	28	9	4	46	2	48	8	11	1	0	9	16	14	5	7	20
Load Containers & Attachments																					
• Nets	17	6	9	3	12	7	2	2	15	2	15	0	0	0	0	19	0	13	0	0	10
• Other Mechanical	1	0	1	0	0	0	1	0	1	0	1	0	0	0	1	0	0	0	0	0	2
Subtotal	18	6	10	3	12	7	3	2	16	2	16	0	0	0	1	19	0	13	0	0	12
Human Error																					
• Pilots	16	1	6	9	4	8	6	10	6	7	9	5	6	0	1	2	2	3	2	7	8
• Pilot/Air Crew	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
• Air Crew	2	0	0	1	0	2	0	0	2	0	2	0	1	0	0	1	0	0	0	0	2
• Ground Crew	5	0	2	0	0	5	0	0	5	0	5	0	0	0	0	1	4	0	0	0	0
Subtotal	23	1	8	10	4	15	6	10	13	7	16	5	7	0	1	4	6	3	2	7	10
Total Percent	100	16	65	18	27	55	18	16	84	12	86	14	23	2	2	35	23	30	10	15	45
			99			100		100		100				99					100		

TABLE VIII

SUMMARY OF 131 MARINE/NAVY CH-53 EXTERNAL CARGO FAILURES

Vietnam	95%
Other Locations	5%
Documented Failure Reports	100%
Recitations of Personal Experience	0%
Other	0%

	Percentage of All Failures																
		By Task Progression			By Load Density			By Load Stabilization		By Environment		By Load Types					
Causes of Failure	Total	Picking Up	Cruising – In-Flight	Delivering	Class I High Density	Class II Medium Density	Class III Low Density	Problems Encountered	No Problems Encountered	Adverse	Not Adverse	Aircraft Recoveries	Single Unsupported	Containers	Pallets	Nets	Strapped
Aircraft Subsystem																	
• Hook Load Release & Controls	4	2	0	2	0	2	2	0	4	0	4						
• Winch	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA						
• Pendants	5	2	3	0	0	8	0	0	5	0	5						
Total	9	4	3	2	0	10	2	0	9	0	9						
Rigging																	
• Slings	33	9	24	0	3	23	2	1	32	0	33						
• Straps	6	0	6	0	0	5	7	2	4	0	6						
• Doughnuts	1	0	1	0	0	2	0	0	1	0	1						
• Clevis	0	0	0	0	0	0	0	0	0	0	0						
• Other Mechanical	0	0	0	0	0	0	0	0	0	0	0						
Total	40	9	31	0	3	30	9	3	36	0	40						
Load Containers & Attachments																	
• Nets	4	0	3	1	0	2	0	0	4	0	4						
• Other Mechanical	2	2	1	0	0	2	2	0	2	0	2						
Total	6	2	4	1	0	4	2	0	6	0	6						
Human Error																	
• Pilots	27	12	7	7	5	3	18	11	16	7	20						
• Pilot/Air Crew	3	3	0	2	0	0	2	0	3	2	1						
• Air Crew	1	0	0	0	0	0	0	0	1	0	1						
• Ground Crew	15	5	7	3	5	5	3	2	13	0	15						
Total	46	20	14	12	10	8	23	13	33	9	37						
Total Percent	101	35	52	15	13	52	36	16	84	9	92						
			102			101		100		101							

Insufficient Data

TABLE IX

SUMMARY OF 40 ARMY CH-54 EXTERNAL CARGO FAILURES

Vietnam 95%; Other Locations 5%; Documented Failure Reports 0%; Recitations of Personal Experience 50%; Other 50%	Percentage of All Failures																
		By Task Progression			By Load Density			By Load Stabilization		By Environment		By Load Types					
Causes of Failure	Total	Picking Up	Cruising – In-Flight	Delivering	Class I High Density	Class II Medium Density	Class III Low Density	Problems Encountered	No Problems Encountered	Adverse	Not Adverse	Aircraft Recoveries	Single Unsupported	Containers	Pallets	Nets	Strapped
Aircraft Subsystem																	
• Hook Load Release & Controls	18	0	15	3	13	5	0	0	18	0	18	3	15	0	0	3	0
• Winch	3	0	3	0	0	3	0	0	3	0	NA	NA	0	0	0	0	0
• Pendants	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Total	21	0	13	3	13	8	0	0	21	0	21	3	15	0	0	3	0
Rigging																	
• Slings	23	5	18	0	13	5	3	0	23	0	23	3	8	0	3	8	3
• Straps	3	0	3	0	3	0	0	0	3	0	3	0	0	0	0	0	3
• Doughnuts	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
• Clevises	5	3	3	0	5	0	0	0	5	0	5	0	3	0	0	3	0
• Other Mechanical	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	31	8	24	0	21	5	3	0	31	0	31	3	11	0	3	11	6
Load Containers & Attachments																	
• Nets	8	0	8	0	8	0	0	0	8	0	8	0	0	0	0	8	0
• Other Mechanical	5	3	0	3	3	3	0	0	5	0	5	0	0	0	5	0	0
Total	13	3	8	3	11	3	0	0	13	0	13	0	0	0	5	8	0
Human Error																	
• Pilots	30	13	0	18	20	5	5	20	10	8	22	5	15	0	0	3	3
• Pilot/Air Crew	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
• Air Crew	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
• Ground Crew	5	5	0	0	3	3	0	0	5	0	5	0	5	0	0	0	0
Total	35	18	0	18	23	8	5	20	15	8	27	5	20	0	0	3	3
Total Percent	100	28	48	23	68	23	8	20	80	8	92	10	49	0	8	23	8
			99			99		100		100				98			

TABLE X

OVERALL SUMMARY OF 371 ARMY AND NAVY/MARINE EXTERNAL CARGO HANDLING FAILURES INVOLVING THE CH–46, 47, 53, AND 54 HELICOPTERS

Causes of Failure	Total Failures: Average	Total Failures: Helos with Minimum Experience	Total Failures: Range	Total Failures: Helos with Maximum Experience	Percentage of All Failures — By Task Progression: Picking Up	Cruising - In Flight	Delivering	By Load Density Omitting the CH-46: Class I High Density	Class II Medium Density	Class III Low Density	By Load Stabilization: Problems Encountered	No Problems	By Environment: Adverse	Not Adverse	By Load Types: Aircraft Recoveries	Single Unsupported	Containers	Pallets	Nets	Strapped
					Average Experience for All Helicopters										CH-47 and 54 Only					
Aircraft Subsystem																				
● Hook Load Release & Controls	12.8	CH-53	4 to 26	CH-46	2.8	6.3	3.7	4.1	6.4	2.3	0.3	12.5	0.5	12.3	1.7	8.6	0.8	0	1.7	0
● Winch	0.3	used only on CH-54			0	0.3	0	0	0.3	0	0	0.3	0	0.3	0.3	0	0	0	0	0
● Pendents	3.1	used and consistent only for CH-46 & CH-53			0.7	2.4	0	0	3.1	0	0	3.1	0	3.1	0.4	0.7	0.1	0.1	1.1	0.7
Subtotal	16.2	CH-47 & 53	9 to 31	CH-46	3.5	9.0	3.7	4.1	9.8	2.3	0.3	15.9	0.5	15.7	2.4	9.3	0.9	0.1	2.8	0.7
Rigging																				
● Slings	26.2	CH-46	13 to 33	CH-53	5.8	19.4	0	5.4	18.0	1.8	0.6	24.6	0.3	24.9	1.7	10.1	0	1.0	7.0	5.4
● Straps	6.5	CH-46	3 to 12	CH-47	1.3	5.2	0	0.7	2.6	3.2	1.2	5.3	0	6.5	2.3	0	0	0	0	4.2
● Doughnuts	3.1	CH-46 & 53	1 to 8	CH-47	0	3.1	0	0.3	2.2	0.6	0.3	2.8	0.3	2.8	0.5	0.4	0.4	0	0.9	0.9
● Clevises	1.0	CH-53	0 to 5	CH-54	0.2	0.8	0	1.0	0	0	0	1.0	0	1.0	0	0.6	0	0	0.4	0
● Other Mechanical	0.3	–	–	–	0	0.3	0	0	0	0.3	0	0.3	0	0.3	0.3	0	0	0	0	0
Subtotal	36.1	CH-46	18 to 50	CH-47	7.3	28.8	0	7.4	22.8	5.9	2.1	3'0	0.6	35.5	4.8	11.1	0.4	1.0	8.3	10.5
Load Containers & Attach.																				
● Nets	6.9	CH-46	0 to 17	CH-47	1.5	4.2	1.2	3.9	2.5	0.5	0.5	6.4	0.5	6.4	0	0	0	0	6.9	0
● Other Mechanical	2.3	CH-46	0 to 5	CH-54	1.6	0.7	0	0.3	1.0	1.0	0	2.3	0	2.3	0	0	0	2.3	0	0
Subtotal	9.2	CH-46	3 to 18	CH-47	3.1	4.9	1.2	4.2	3.5	1.5	0.5	8.7	0.5	8.7	0	0	0	2.3	6.9	0
Human Error																				
● Pilots	24.1	CH-47	16 to 30	CH-54	8.3	5.9	9.9	7.0	5.2	11.9	10.6	13.5	7.6	16.5	6.4	11.0	0	0.9	2.9	2.9
● Pilot/Air Crew	6.2	CH-47 & 54	0 to 19	CH-46	2.2	0	4.0	1.5	0	4.7	0	6.2	4.5	1.7	0.9	1.5	0.1	0.1	2.2	1.4
● Air Crew	0.6	–	–	–	0	0	0.6	0	0.6	0	0	0.6	0	0.6	0	0.3	0	0	0.3	0
● Ground Crew	8.5	CH-46 & 47 & 54	5 to 15	CH-53	3.1	4.2	1.2	2.7	4.4	1.4	0.7	7.8	0	8.5	0	2.4	0	0	1.2	4.9
Subtotal	39.4	CH-47	23 to 50	CH-46	13.6	10.1	15.7	11.2	10.2	18.0	11.3	28.1	12.1	27.3	7.3	15.2	0.1	1.0	6.6	9.2
Total Percent	100.9				27.5	52.8	20.6	26.9	46.3	27.7	14.2	86.7	13.7	87.2	14.5	35.6	1.4	4.4	24.6	20.4
						100.9			100.9		100.9		100.9				100.9			

helicopter: 12 pilots and 21 air crewmen. Subsequently, corollary data were obtained from seven experienced CH-54 pilots. This data base is very thin, and we cannot place extensive credibility on it, although we feel it is helpful. We wish to correlate this opinion data with our data on actual specific failures taken from the preceding section of this chapter – Summary of the Causes of Specific Failures Experienced. When the consensus agrees well with the data from the analysis of specific failures, the validity of both are reinforced. Where they disagree, one may question either and look for reasons for the disagreement.

Our initial approach was to ask the interviewees three series of questions to see how simplistic or complex they perceived the cause of failures to be. As will be shown below, we found that they perceived the system to be complex – which is correct, for it is a complex system.

First of all, we asked them to focus simplistically on just the immediate people and equipment in the system as the principal cause of failures. There was no consensus (2-½ to 1 range), but the average estimate indicated that human error accounted for a low 15% and mechanical failures 85% of the overall failures experienced.

Secondly, we asked the same interviewees to expand their concept of the system to include failures due to calculated risks taken. In this case the human error-to-mechanical failure ratio reversed proportionately. There was a good consensus that human error was 52% and mechanical failure 35%. There was not a consensus on the percentage of failures that they felt could be assigned to calculated risk alone; it varied from negligible to 23%, averaging 13%.

Thirdly, we asked the same group again to expand their concept of the system to include secondary causes of failures, such as adverse weather and terrain, inadequate supplies of rigging materials, and the like. In this case their opinions of both human error and mechanical failures became very diffuse (far from a consensus). Estimates of human errors remained high, averaging 45%, mechanical failures dropped to 24%, and they thought the other causes were responsible for 31% of the overall failures.

The foregoing points out that if the causes of failures are traced back far enough, all failures can ultimately be interpreted as human error. For this reason, for the purposes of this study it was very necessary to be precise in thinking of human errors as just those committed by people who were actually parts of the system – the pilots, the air crew, and the ground crew. Moreover, it was also necessary to consider the performance of these people within normal performance envelopes.

Finally, we omitted human error entirely from our questionnaire and asked the respondents to estimate the apportionment of mechanical failures only. Table I tabulates the results and compares the consensus of just mechanical failures against the corollary summary data of actual failures taken from Section E. One fact stands out, viz., that pilots and air crewmen are substantially more optimistic about the reliability of the helicopter subsystem than the evidence seems to warrant. To compensate for what is perhaps an unwarranted optimism, they are somewhat unduly pessimistic about certain system components external to the helicopter. They appear to focus negatively on very specific components and are realistic about most others. For the CH-47, the crews are pessimistic about nets, while almost completely overlooking a significant problem with straps. For the CH-54, the crews are pessimistic about slings and reasonably realistic in all other areas.

G. SUMMARY OF COMPARABLE CARGO-CARRYING EXPERIENCE

During the course of our study we also interviewed personnel of the Helicopter Association of America and six commercial cargo helicopter concerns. The consensus of their people was that two principal problems predominate. In order of importance they are:

1. *Load Stabilization/Pilot Error* – Pilots often have to fly loads and then reland to readjust them so they can be flown properly. Moreover pilots often fly or maneuver too fast for a given load, lose control of the load, and then have to abort it. This happens most frequently with light and bulky (low-density) loads.

2. *Hook Problem* – The hook problem is twofold: (a) the load release mechanisms often fail, causing the load to drop; and (b) the design of the release switches and mechanisms from a human factors standpoint is poor. The activation switches are felt to be too accessible and amenable to inadvertent activation.

The interviews also accentuated three major differences between commercial and Army practices. They are:

1. The rigging practice is noticeably different. The commercial operators use pendants and/or configurations, like the California H-frame, that allow them to stay well above the load. Because of this type of rigging, there is less tendency to effect IFR conditions because of dust. Failed rigging, they feel, is less apt to damage the aircraft if it breaks and springs back. In addition, they always use a low-torque swivel that prevents the rigging from twisting up. This point was emphasized by almost all the persons interviewed. They stressed that they used large

antifriction bearing swivels that impart a very low torque on the rigging even when extremely heavy loads rotate in flight. With respect to this point, it is interesting to note that the Army practice is also somewhat different from Navy/Marine practice, with that of the latter coming closer to commercial practice. The Navy uses an 8-foot-long pendant with a swivel and a hook capable of being opened from the helicopter by means of a mechanically actuated lanyard. However, the swivel in this pendant is far from the low-torque unit described by commercial interviewees.

2. Slings and pendants used consisted almost totally of wire rope as opposed to the nylon used by the military. Almost all of those persons interviewed were convinced that the high elasticity of nylon causes or permits vertical bounce, is therefore hazardous, and should not be used, except when working adjacent to high-voltage power lines when the added risk in their minds would be justified. (This theory is inconsistent with Army and airframe manufacturers' studies of the subject.)

3. The commercial communication/guidance scheme is also noticeably different from that of the military, the principal difference being that ground crewmen employing hand signals for guidance are not utilized. This is interesting because many military pilots have told us that they have found the hand signal practice unreliable. Principally, they cannot tell which of a number of ground crewmen waving their hands (none of whom seem to know the helicopter must fly into the wind) is supposed to be guiding them.

4. The commercial operators use a cargomaster who is stationed with the load and is in direct radio contact with the pilot. In this procedure, the guidance comes from the load center, and is more direct and precise than outboard guidance by hand signal. In addition, this method does not require that the pilot take his eyes off his visual reference points – his instruments and controls.

We also reviewed a series of reports entitled "Briefs of Accidents Involving Rotocraft," U.S. General Aviation, for the years 1966 through 1969, published by the National Transportation Safety Board. The last year for which they analyzed and published such data to date was 1969.

Applying our definition of a failure, we found 24 failures/accidents and coded the pertinent information for each. The results are interesting but difficult to relate to military experience. These data are really too thin to draw hard conclusions, so the following should be thought of as hypothetical.

The average commercial pilot incurring an external cargo-carrying accident appears to be a mature, experienced man flying a small helicopter with a light load (under 1000 lb) and prone to human error, particularly while landing when his overall visibility is far from adequate (cannot see below or behind him). Mechanical failures appear to have little influence on the overall number of accidents experienced.

Accidents occurring while delivering a load predominated in the period studied, but there is some evidence that, as time passes, accidents are becoming distributed more uniformly throughout the flight.

The average age of the pilots incurring an accident was 36 years (range 23 to 52). He had an average of 3400 total flight hours (274 to 12,000) and an average of 633 hours in type (30 to 1747). These averages represent considerable flight time if one remembers that the average Army CH-47 pilot logged about 500 to 600 hours during a year's tour in Vietnam. In only 5 of the 24 accidents/failures did the pilot have under 1000 total hours and/or 100 hours in type. In only one accident did they both occur simultaneously.

Most all of the commercial aircraft experiencing failures/accidents were relatively small, vintage reciprocating-engine-driven models. Some 83% were small two-seaters with perhaps 500 to 1000 pounds of payload capacity. The principal aircraft among those studied were of the Bell 47G series. Some 13% were Bell 204B and 205A models similar to the early UH-1's (Iroquois). These have a maximum payload capacity of between 3500 and 4500 pounds. One was a Sikorsky S58-B (similar to the UH-34) with a payload capacity of about 5000 pounds. None approached the Chinook (CH-47) capacity (10,600 to 12,700 lb), although it is known that significant quantities of CH-37's and at least one CH-54A are now in the hands of commercial operators (9,000- and 19,500-pound capacities, respectively).

In only one case (4%) was the failure/accident initiated, but not completely caused, by an equipment failure (broken sling). In another two cases (8%) accidents/failures were caused by human error but compounded by failures of the hook to open. All others, or about 88%, of all the commercial accidents/failures analyzed were caused by pure pilot error.

V. DATA ANALYSIS

A. FAILURE OCCURRENCES

Actual failure occurrences as functions of load density carried and flight progression for the individual helicopters under consideration are presented in Figures 1 and 2 . The reader should recognize that all these data represent distributions of failures as experienced by typical helicopters of that type as it was typically utilized in Vietnam. Thus, since each helicopter carried different distributions of loads in terms of configuration, densities, rigging, and load containment practices, the data should not be construed as failure rates and are not directly relatable from helicopter to helicopter. Nevertheless, read with a background understanding of the different ways in which the various helicopters were utilized, it is an extremely valuable body of data.

Table XI presents a scaling of the principal causes of failures presented in Figures 1 and 2 . The largest single cause of failure in any helicopter, as indicated, was the sling in the CH-53 (33% of overall failures). These scalings were made both for specific helicopters (from which the maximum scale of 10 was derived) and for the average of the four helicopters. A scale of 10 means the maximum failure occurrences experienced; zero means an insignificant number was experienced.

Some interesting observations can be drawn from Table XI. First, slings and pilot errors stand out as the two largest – and about equal in magnitude – causes of failures. This is doubly interesting since the two are so strongly interrelated (a pilot can probably break almost any sling just by flying too fast). Secondly, hook failures appear to be substantial. Thirdly, there are four other significant causes of failures which are about equal in magnitude – straps, nets, pilot/air crew (guidance/collison) errors, and ground crew (rigging) errors.

We feel that the most important general observation that can be made from Table XI is that mechanical failures predominantly occur in flight. A second most important observation is that pilot error appears to be the predominant cause of failure when low-density loads are being carried.

Certain observations can also be made concerning the cause of failures in specific helicopters. For instance, the CH-53 and CH-54 have basically the same hook. Therefore, the significantly larger number of hook failures shown for the CH-54 can be assumed to be caused by the swivel commutator and electrical equipment unique to it.

TABLE XI

SCALING OF TYPICAL CAUSES OF FAILURES IN EXTERNALLY LOADED HELICOPTERS IN VIETNAM

Cause of Failure	Average of Four Helicopters							When Load Stabilization Problems Occur	When Adverse Environmental Conditions Exist	For Specific Helicopters			
		By Task Progression			By Load Density								
	Overall	Picking-up	In Flight	Delivering	Low Density	Medium Density	High Density			CH-46	CH-47	CH-53	CH-54
Helicopter Subsystem													
• Hook	4	1	2	1	1	2	1	0	0	8	3	1	5
• Winch	0	0	0	0	0	0	0	0	0	NA	NA	NA	1
• Pendants	1	0	1	0	0	1	0	0	0	2	NA	2	NA
Rigging													
• Slings	8	2	6	0	1	5	2	0	0	4	8	10*	7
• Straps	2	0	2	0	1	1	0	0	0	1	4	2	1
• Doughnuts	1	0	1	0	0	1	0	0	0	0	2	0	NA
• Clevises	0	0	0	0	0	0	0	0	0	0	0	0	2
Load Containers & Attachments													
• Nets	2	0	2	0	0	1	1	0	0	0	5	1	2
Human Error													
• Pilot	8	3	2	3	4	2	2	3	2	8	5	8	9
• Pilot/Air Crew	2	1	0	1	2	0	0	0	1	6	0	1	0
• Air Crew	0	0	0	0	0	0	0	0	0	0	1	0	0
• Ground Crew	2	1	1	0	0	1	1	0	0	2	2	5	2

Notes: *Related to the Maximum Single Cause of Failure, Sling Failures in the CH-53 = 10.

The high number of sling failures in the CH-53 may be related to the correspondingly high number of ground crew errors associated with this helicopter.

Net failures are almost unique to the Army and significant only with the CH-47. We do not believe the Navy uses nets to any extent. Similarly, strap failures on the CH-47 are the most significant of any of the other helicopters' experience.

Certain of the data from Table XI perhaps can be questioned. For instance, the CH-46 appears to have had an extraordinarily great number of hook failures. Pilot/air crew guidance errors also appear substantial and almost unique to this aircraft. However, our data base for this aircraft contains an atypically high number of failures relating to CONUS training experience (46% vs. about 5% for other helicopters analyzed). Thus, this high rate of failure occurrences may very well be an artifact of the data – something that happens principally in training.

B. FAILURE RATES

Failure occurrence data were developed in Section A, and failure rate data will be developed in this section. Both are based on combat support experience of particular helicopters in Vietnam, principally in the time frame of 1968 through 1971. Both are important in that they offer unique kinds of information:

- Failure occurrence data indicated the particular causes of failure by system element (rigging, aircraft component, etc.) by helicopter type.

- Failure rate data relate the incidence of failure to a common operational measurement (i.e., sorties) for each helicopter type. Failures per sortie can be readily converted into a measurement tool of more general use (i.e., failures per 100,000 hours) since the relation between hours and sorties is known for each helicopter.

A failure occurrence can be focused on a helicopter's own actual problems within the universe of its problems, but sight is lost as to whether these problems are greater or less than the universe of all helicopter experience. Failure rates relate failures to a universal dimension (occurrences per sortie), so that the experience of the various helicopters could be compared (if we had sufficient data, which we do not), or the experience of a single helicopter could be compared under various operating modes (for which we have sufficient data).

Unfortunately, we have insufficient data to develop relatively comprehensive failure rate data for any but the CH-47 helicopter. We can estimate the mean failure rate of the CH-54 reasonably well, but we have insufficient data on the Marine CH-46 and CH-53 helicopters even to guess at their mean failure rates. For these reasons we must be content with developing and utilizing failure rate data on the CH-47. Our method of using these data will be to compare failure rates by load types, load densities, and flight progression. This is an extremely useful exercise, as it allows one to forecast what effect certain changes would have on the system. For instance, what attenuation in mean failure rate would occur if high-density loads were no longer carried in nets.

The fact that we are able to concentrate on the CH-47 is fortuitous in that 81% of all the cargo carried in the peak years of 1968 and 1969 in Vietnam were carried by this helicopter.

1. Mean Failure Rate

The starting point in developing failure rate data is to develop the mean failure rates of the helicopters of interest. In this case we will concentrate on the CH-47, but for comparative purposes we will also estimate the mean failure rate of the CH-54.

It is convenient to define a mean failure rate as follows:

$$\lambda_m = \frac{\text{total number of lift system failures/unit time}}{\text{total number of cargo sorties/unit time}}$$

We have previously defined six categories of external loads. In this section we will examine the discrete failure rate by category. We define the discrete failure rate for Category I (for example) as:

$$\lambda_d = \frac{\text{number of lift system failures attributable to Category I/unit time}}{\text{number of Category I sorties/unit time}}$$

It is apparent that the value of mean failure rate is determined by the distribution by load categories in the total population.

We can establish that the average CH-47 company flew 1447 cargo sorties per month carrying approximately 5000 pounds per sortie. (See data from Figure 21 for 21 companies present in Vietnam at that time.)

The mean failure rate fixes for the CH-47 are as follows:

- Pilot Consensus Data (10)

$$\lambda_m = \frac{2.15 \text{ failures/mo./company}}{1447 \text{ sorties/mo.}} = 1.49 \times 10^{-3} \text{ failures/sortie}$$

- Aircrew Member Consensus (11)

$$\lambda_m = \frac{5}{1447} = 3.45 \times 10^{-3} \text{ failures/sortie}$$

- 1st Brigade Report

Some 57 failures were reported in a 3.5-month period (June – September 1968) from 11 reporting companies:

$$\lambda_m = \frac{57}{3.5 \times 1447 \times 11} = 1.02 \times 10^{-3} \text{ failures/sortie}$$

- From CH-47 100-Bit Failure Information

$$\lambda_m = \frac{5.1}{1447} = 3.52 \times 10^{-3}$$

The mean failure rate for the CH-54 is based on reports of a total of 8 failures in an average 11-month tour made by six pilots. This is equivalent to 1.33/11 = 0.12 failures/pilot/mo. or 0.12 x 18 = 2.16 failures/company/mo.

$$\lambda_m = \frac{2.16}{774} \frac{\text{failures/company/mo.}}{\text{sorties/mo.}} = 2.79 \times 10^{-3}$$

Figure 27 is a bar chart displaying the mean failure rates. For future reference we select the average of these means as representative:

$$\lambda_{mm} = 2.37 \times 10^{-3} \text{ for the CH-47, and}$$

$$\lambda_{mm} = 2.79 \times 10^{-3} \text{ for the CH-54.}$$

One can see from Figure 25 that our confidence on the CH-47 failure rate is in the order of ± 60%, while we have no sense of limits on the CH-54 failure rate, as it was derived from a single (and small) body of data.

2. Distribution of Mean Failure Rates by Company

The mean failure rate sample cited from the 1st Brigade has the following distribution by company. Assuming the sortie generation rate was the same for each company and identically equal to 1447 sorties per month, the mean failure rate per company can be calculated as follows:

$$\lambda_m = \frac{\text{failures reported}}{1447 \text{ sorties/mo.} \times 3.5 \text{ mo.}} \text{ failures/sortie}$$

Company	Failures	λ_m
213th ASHC	9	1.78
147 ASHC	2	0.39
242 ASHC	16	3.16
243 ASHC	1	0.20
271 ASHC	1	0.20
132 ASHC	12	2.37
179 ASHC	7	1.38
205 ASHC	2	0.39
178 ASHC	3	0.59
196 ASHC	1	0.20
273 ASHC	1	0.20

It can be seen that the range of failure rate experience was very great. In this case the failure rates varied by a ratio of nearly 16 to 1.

3. Failure Rate by Load Category

Table XII indicates the load distribution for CH-47's operating in Vietnam as determined by aircrew members' experience (consensus data). It lists the CH-47 lift system failures evaluated in Section A (Summary of 100 CH-47 External Cargo Failures). The 100 failures studied must have come from a total population of:

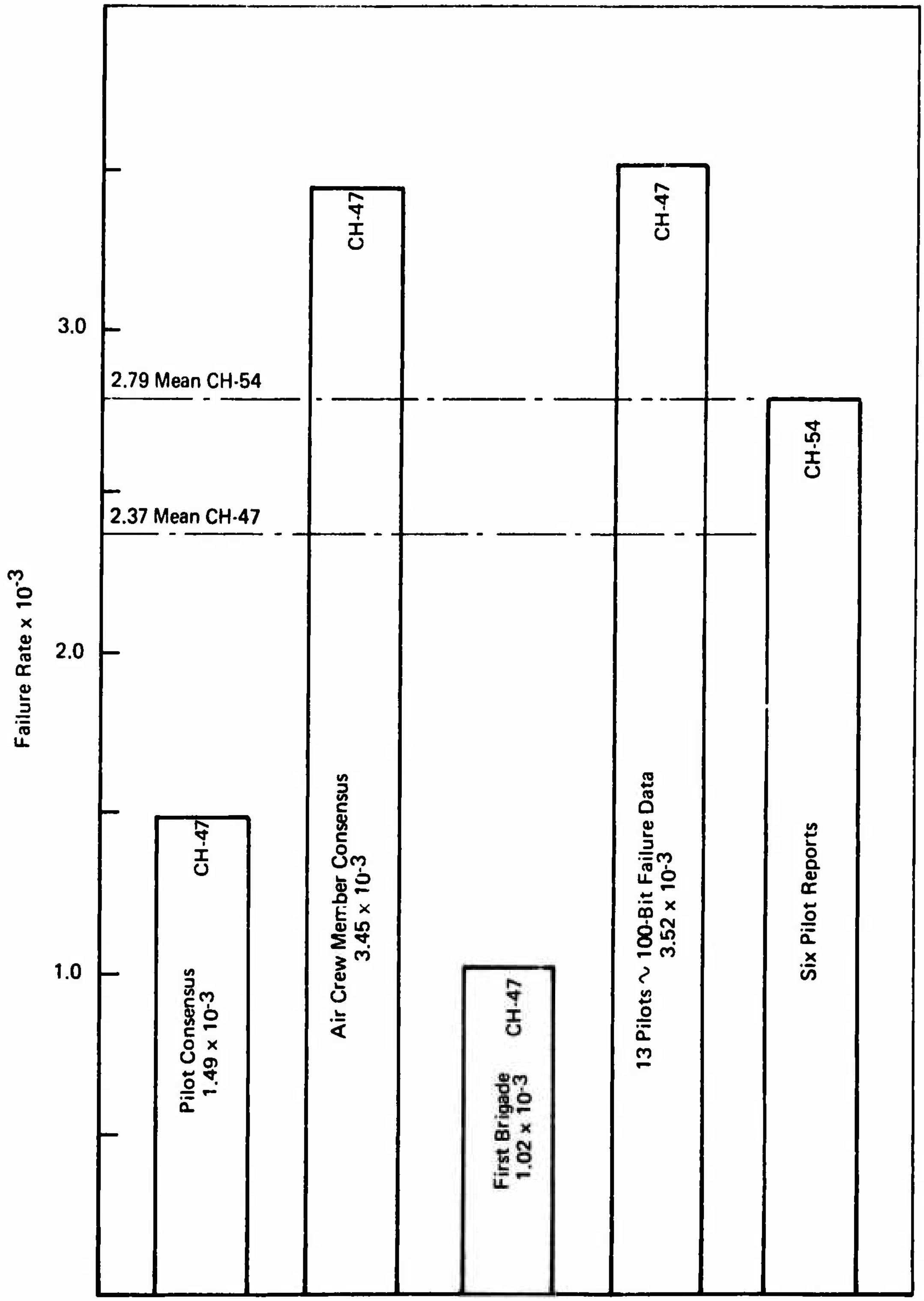

FIGURE 25. DERIVATION OF MEAN FAILURE RATES FOR THE CH-47 AND CH-54 HELICOPTERS.

$$\frac{100}{2.37 \times 10^{-3}} = 42{,}194 \text{ sorties}^{*}$$

Failure rates are identically the ratio of losses reported to number of sorties by category.

TABLE XII

CH-47 LOAD DISTRIBUTION PROFILE

Category	Load Distribution	Number of Sorties	Reported Failures	Failure Rate x 10^{-3}
1	7.3	3,080	14	4.54
2	28.8	12,152	23	1.89
3	11.7	4,937	2	0.405
4	14.1	5,950	2	0.336
5	32.7	13,797	35	2.54
6	5.8	2,447	23	9.40
			99	2.37×10^{-3}

Even though the sample size is small, it is nonetheless possible to determine what mechanical and human failings contributed to the discrete failure rate by category. For example, in Table XIII (Summary of Rates Associated with 100 Army CH-47 External Cargo Failures), we note the following distribution of contributors to the Category I failures: 1 hook, 1 sling, 5 straps, 1 doughnut, 1 other mechanical, and 5 pilot errors, for a total of 14 failures. The base failure rate is 4.54×10^{-3}. Evidently each unit contributor is worth

$$\frac{1}{14} \times 4.54 \times 10^{-3} = 0.324 \times 10^{-3}$$

Thus the hazard rate attributable to hooks while carrying a disabled A/C (Category I) is $1 \times 0.324 \times 10^{-3}$ failures/sortie.

Figure 3 displays basically the same data as Figure 25 in a more graphic bar chart format.

4. Failure Rates by Sortie Progression and Load Density

We would also like to examine failure rates as a function of the sortie (flight) progression and by varying load densities. The former exercise is relatively

*See Load Distribution, Chapter IV-D.

TABLE XIII

SUMMARY OF RATES ASSOCIATED WITH 100 ARMY CH-47 EXTERNAL CARGO FAILURES

Point of Failure	Total	Failure Occurrences By Load Types * Aircraft Recoveries	Single Unsupported	Containers	Pallets	Nets	Strapped	Failure Rate x 10^{-3} By Load Types * Aircraft Recoveries 1	Single Unsupported 2	Containers 3	Pallets 4	Nets 5	Strapped 6
Aircraft Subsystem													
• Hook Load Release & Controls	9	1	5	1	0	1	0	.324	.410	.202	–	.072	–
• Winch	NA	NA	NA	NA	NA	NA	NA						
• Pendants	NA	NA	NA	NA	NA	NA	NA						
Rigging													
• Slings	28	1	10	0	0	6	6	.324	.822	–	–	.435	2.45
• Straps	12	5	0	0	0	0	8	1.621	–	–	–	–	3.26
• Doughnuts	8	1	1	1	0	2	2	.324	.082	.202	–	.145	.817
• Clevises	1	0	0	0	0	1	0	–	–	–	–	.072	–
• Other Mechanical	1	1	0	0	0	0	0	.324	–	–	–	–	–
Load Containers Attachments													
• Nets	17	0	0	0	0	19	0	–	–	–	–	1.379	–
• Other Mechanical	1	0	0	0	1	0	0	–	–	–	.168	–	–
Human Error													
• Pilots	16	5	6	0	1	2	2	1.621	.493	–	.168	.145	.817
• Pilot/Air Crew	0	0	0	0	0	0	0	–	–	–	–	–	–
• Air Crew	2	0	1	0	0	1	0	–	.082	–	–	.072	–
• Ground Crew	5	0	0	0	0	1	4	–	–	–	–	.072	1.63
Total	100	14	23	2	2	33	22	4.54	1.89	.405	.336	2.54	9.40
				99									

*Rounded Off

straightforward. We have selected a mean failure rate of 2.37×10^{-3} as representative of CH-47 experience in Vietnam, and we know that every sortie progression sequentially passed through pickup, cruise flight, and delivery. From the CH-47 100-bit failure data we have a representative breakdown of failures experienced in each phase of flight. The 100 failures occurred in 42,194 sorties. Each of the 42,194 sorties consisted of a takeoff, a cruise, and a landing phase. Since we know in which phase each failure occurred, we can calculate failure rates attributable to each failure element (i.e., rigging, nets, human error, etc.) by phase of flight.

Arriving at failure rates as a function of load densities is much more difficult. Unlike sortie progressions, we do not immediately know what the breakdown of load densities carried in Vietnam was. Therefore, we are forced to develop this information somewhat obliquely.

Load density is load weight divided by the projected frontal area. We have some data on load weight distribution, so we can see if we can estimate load density distributions from it. We know that the CH-47 B/C had maximum payload capacities of about 19,000 pounds. Therefore, we can say that all the loads varied between 0 and 19,000 pounds. We also developed information in Chapter IV that identified the average load carried in 1968 and 1969 as weighing 4900 pounds. From this information, we can approximate a load distribution curve for the CH-47 (see Figure 26). This curve is simply a sensibly proportioned representation that extends from 0 to 19,000 pounds, peaks at 4900 pounds, and has an area under the curve below 4900 pounds which equals the area over 4900 pounds.

Now we would like to divide this curve into areas that relate to high, medium, and low densities. To assist in this task, we analyzed 159 military vehicles and equipments commonly carried as CH-47 external loads. By weight, they broke down into density categories as follows (the density category limits are shown in Figure 26).

	Weight (lb)		
Density Category	**Minimum**	**Maximum**	**Average**
I – High	4,100	18,000	11,753
II – Medium	2,350	14,460	5,976
III – Low	1,130	4,400	3,055

We have also plotted these distributions and their averages in Figure 26. It can be seen that on the average there is some clear proportionality between load weight and load density. It appears reasonable, from all the data, that one can define the limits of medium density at the extreme end of the low-density weight

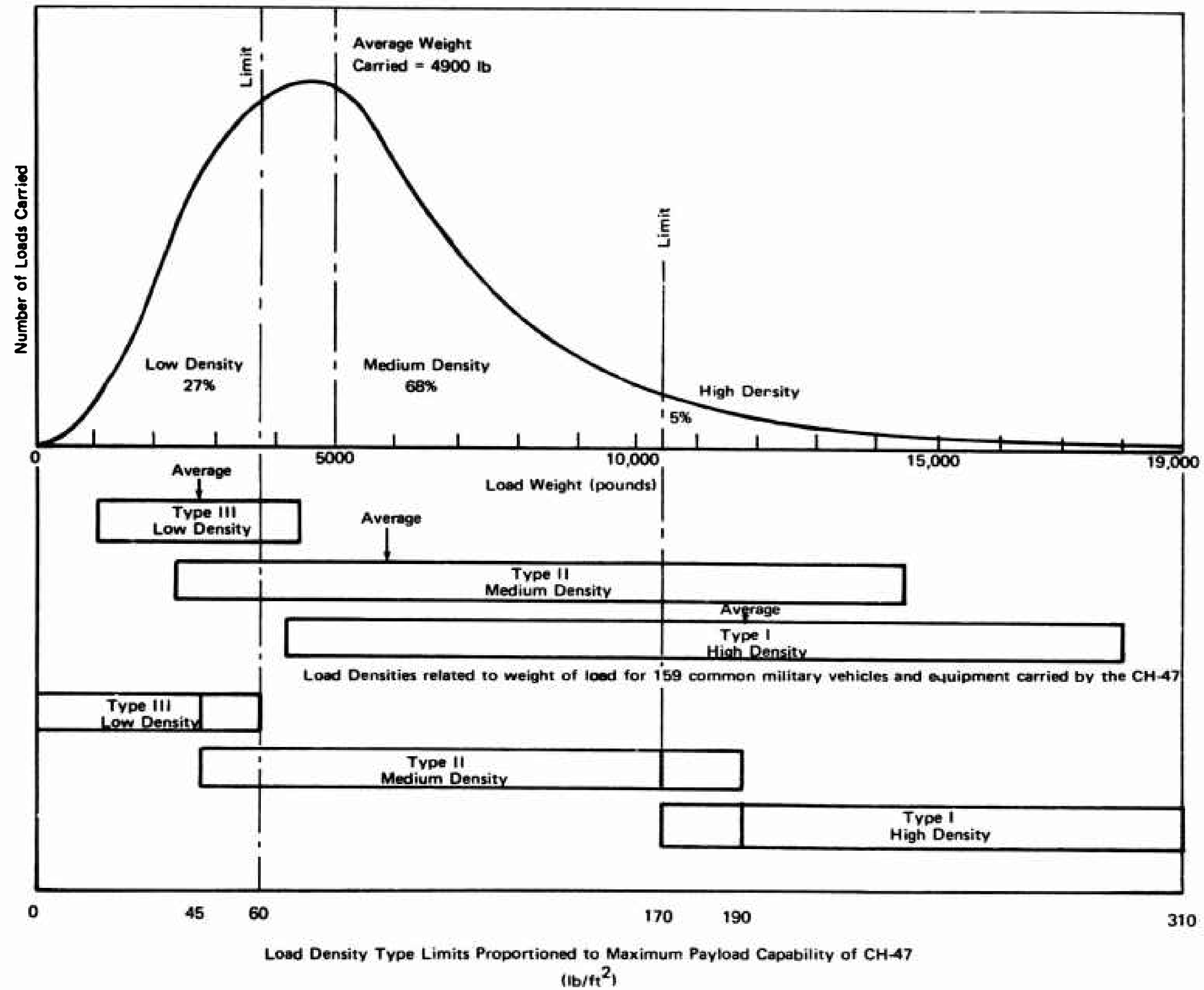

FIGURE 26. DERIVATION OF LOAD DENSITIES FOR THE CH-47 HELICOPTER IN VIETNAM.

range. These translate proportionately to about 3700 pounds and 10,300 pounds, respectively.

Taking these limits and measuring the areas under the curves, we estimated that the CH-47 carried:

27% low-density loads,
68% medium-density loads, and
5% high-density loads.

These percentages appear realistic in the light of interview information from experienced CH-47 pilots.

Taking these distributions and inserting these values into Table XIV, we calculated the individual failure rates. As in the case of sortie progression, the overall mean failure rate must be 2.37×10^{-3}.

We then plotted the individual cause of failure rate data in the more graphic bar chart form in Figures 4, 5, and 6.

5. Discussion of Results

We have previously discussed some of the reasons for the wide variability of failure rate levels (such as area of operation, category of loads, etc.). Additionally the sample size is small, particularly when assigning levels attributable to failure elements (parts of rigging, for example). For this reason we have provided additional information on the real number of failures (see Table XII) so that the reader can get a feel for the coarseness of the resulting rate.

The failure rate data shown in Figure 3 lead to some interesting conclusions. Strapped or chained-together loads have, by far, the highest failure rate. Their failure rate is more than double the failure rate of the second most failure-prone load – disabled-aircraft recoveries. In third and fourth place are net loads and single, unsupported loads, respectively, which have failure rates approximately half that for disabled-aircraft recoveries. Container and palletized loads have very low failure rates – a small fraction of any other load category.

There is a disproportionate amount of pilot error involved in aircraft recovery loads. They must be extremely hard to fly.

The high failure rate of strapped-together loads is a dual problem of rigging and human error. It just appears to be a difficult load to keep "glued together" in flight.

TABLE XIV

CH-47 FAILURE RATES BY TASK PROGRESSION AND LOAD DENSITY

Point of Failure	Total	Failure Occurrences* By Task Progression: Picking Up	Cruising – In-Flight	Delivering	Failure Occurrences* By Load Density: Class I High Density	Class II Medium Density	Class III Low Density	Failure Rate x IV^{-3}* By Sortie Progression: Pick Up	Cruise	Deliver	Failure Rate x IV^{-3}* By Load Density: Hi Den.	Med. Den.	Low Den	
Aircraft Subsystem														
• Hook Load Release & Controls	9	0	3	5	1	5	1	–	.071	.118	.47	.18	.083	
• Winch	NA	NA	NA	NA	NA	NA	NA							
• Pendants	NA	NA	NA	NA	NA	NA	NA							
Total	9	0	3	5	1	5	1	–	.071	.118	.47	.18	.083	
Rigging														
• Slings	28	6	24	0	6	18	1	.142	–	–	2.84	.66	.083	
• Straps	12	3	9	0	2	5	5	.071	.213	–	.95	.18	.416	
• Doughnuts	8	0	9	0	1	5	2	–	.213	–	.47	.18	.166	
• Clevises	1	0	1	0	1	0	0	–	.024	–	.47	–	–	
• Other Mechanical	1	0	1	0	0	0	1	–	.024	–	–	–	.083	
Total	50													
Load Containers & Attachments														
• Nets	17	6	9	3	12	7	2	.142	.213	.071	5.68	.26	.166	
• Other Mechanical	1	0	1	0	0	0	1	–	.024	–	–	–	.083	
Total	18													
Human Error														
• Pilots	16	1	6	9	4	8	6	.024	.142	.213	1.89	.29	.499	
• Pilot/Air Crew	0	0	0	0	0	0	0	–	–	–	–	–	–	
• Air Crew	2	0	0	1	0	2	0	–	–	.024	–	.07	–	
• Ground Crew	5	0	2	0	0	5	0	–	.047	–	–	.18	–	
Total	23													
Total Percent	100	16	65	18	27	54	19	.379	1.541	.426	12.79	1.98	1.58	Mean Failure Rate
			99			99		2.37				2.37		Distributed Mean Failure Rate
*Rounded Off								100	100	100	5	68	27	Percent Sortie Distribution
											42,194			Total Sorties Represented

The relatively high failure rate of net loads is attributable principally to failures of the nets themselves.

Figure 5 shows the high failure rates of mechanical component (principally rigging) failures in cruise flight. This reinforces the failure-occurrence data. It shows pilot error as minimal during pickup, increasing during cruise flight, and peaking substantially during delivery. It also shows other human error to be almost insignificant as compared to that of the pilot.

Of paramount interest is the apparent extremely high failure rate associated with high-density loads shown in Figure 6. These loads appear to have failure rates 6 to 8 times those of low- and medium-density loads, respectively. The causes of these high-density load failures are also quite interesting. Net failures are the predominant cause of failure, accounting for 44% of combined causes of failures with these loads. Net failures, in this case, even exceed combined rigging failures at 37% of the total.

These high-density load failures call for further investigation. A number of CH-47 pilots interviewed said that a 10,000- to 12,000-pound net load was extremely common in Vietnam. Even the CH-54, which seldom carried a load weighing less than 13,000 pounds, by our data, experienced 23% of its failures carrying net loads. Therefore, it seems unquestionable that Army high-density net loads were frequent in Vietnam.

The mystery is that there is not a net in the Federal Stock Catalog, nor any other of which we are aware, that has a great enough load rating for these loads. None of the Army manuals at our disposal recommends such a practice. It seems apparent that there was a real combat-intensified need for load containers in Vietnam with the characteristics of nets, and the most practical solution was to use the nets on hand despite their high failure rate.

C. RELATIONSHIP BETWEEN ACCIDENTS AND FAILURES

The relationship between accidents and failures is of interest because the helicopter and its crew are extremely valuable and we wish to know to what extent carrying external loads places them at additional risk. Again we will concentrate on CH-47 experience.

Reexamining the 100 CH-47 failure reports for failures that were also accidents, we found one such occurrence. (An accident is defined by the Army as an occurrence that causes substantial damage to the aircraft.) As we have previously shown, the CH-47 failure rate was 2.37×10^{-3} per sortie. Therefore, this single accident replaces an accident rate of 23.7×10^{-6} per sortie or 1/100 of the failure rate.

We asked the Army Agency for Aviation Safety (USAAVS) to provide us with accident statistics on the CH-47 with and without external loads. These data developed with other data from our analysis in other areas are shown in Table XV. Specifically, we used the USAAVS data on the numbers of accidents by years and categories and JCS-OPREA file data on sorties flown. From the two,we calculated accident rates.

From Table XV we can see that the accident rate while carrying external cargo for the years '68 thru '71 averaged 26×10^{-6} per sortie (range of from 15 to 52). This relates well to the 23.7×10^{-6} per sortie accident rate from our data on 100 failures.

Accident rates while delivering cargo averaged about three times those experienced while either picking up or in cruise flight. There were no accidents in cruise flight during 1968 and 1969, but as the conflict subsequently started to wind down, accidents began to occur at accelerated rates in this phase of flight. By 1970 there were more accidents in cruise flight than for any of the other two phases of sorties. These high accident rates do not appear to be related to any particular load category, and the reason for their occurrence is obscure.

Single unsupported, strapped-together, and net loads were associated with very high accident rates, the former two particularly while delivering (landing). There were no accidents at all with container or pallet loads. Aircraft loads which had a substantial failure rate had a very low accident rate.

Perhaps of paramount interest is the fact that the accident rate while not carrying external cargo is about double that experienced with an external load (26×10^{-6} vs. 59×10^{-6}). The Ch-47 carries external cargo on the average about 45% of all sorties flown. The remaining 55% of the sorties are principally troop-carrying operations but also include internal cargo and other combat and maintenance-check sorties. The data suggest that these other sorties have a higher accident rate because they require many more full landings in rough terrain than is the case for external cargo-carrying sorties.

A joint Army-Navy report* on the UH-1 helicopter showed its accident rate in Vietnam in 1968 to be 100×10^{-6} per sortie. This helicopter operates continuously, very much like the CH-47 would when carrying troops. Its accident rate tends to substantiate that the CH-47 accident rates would be higher in troop-carrying and other combat sorties than when carrying external cargo.

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*Orientation-Error Accidents in Regular Army UH-1 Aircraft during Fiscal Year 1968; Relative Incidence and Cost, NAMRL-1145; USAARL Serial No. 72-5.

TABLE XV

CH-47 HELICOPTER
ACCIDENT EXPERIENCE IN VIETNAM

	Overall Accidents			Accidents While Carrying External Cargo						Load Category		Accident Rates/Sortie x 10^{-6}			
							By Phases of Sortie					By Phases of Sortie			
	Numbers[1] of Accidents	Total[2] Sorties	Accident Rate Per Sortie x 10^{-6}	Numbers[1] of Accidents	Ext. Cargo[3] Carrying Sorties	Accident Rate Per Sortie x 10^{-6}	Pick Up	Cruise	Deliver	No.	Description	Pick Up	Cruise	Deliver	Average Rate
1968	20	587,120	34	4	264,204	15	4	0	11	I	Aircraft	0	1	0	1
1969	24	619,560	39	4	278,802	14	4	0	11	II	Single Unsupporter	1	1	7	9
1970	27	542,675	50	9	244,204	37	4	4	29	III	Containers	0	0	0	0
1971	19	299,843	63	7	134,929	52	7	30	15	IV	Pallets	0	0	0	0
Total or Distributed Average										V	Nets	2	2	3	8
	90	2,049,198		24	922,139		5	5	16	VI	Strapped	1	1	7	9
												5	5	16	26

- accident rate while carring external cargo = 26×10^{-6}/sortie
- accident rate while not carring external cargo = 59×10^{-6}/sortie
- average accident rate carring external cargo = 44×10^{-6}/sortie
- failure rate while carring external cargo = $2{,}370 \times 10^{-6}$/sortie

2.3:1

91:1

1. From U.S. Army Agency for Aviation Safety (USAAVS) data
2. From JCS OPREA File data
3. Estimated to be 45% of total sorties flown.

Also from the UH-1 data we found that minor accidents were an insignificant (3.3%) fraction of the total. The average UH-1 accident in Vietnam cost $140,158 or about one-third the replacement cost of the helicopter. Projecting a similar experience for the CH-47, we would expect the average CH-47 accident to cost $600,000 to $700,000. Since an accident occurs about once every 90 failures, its distributed cost would be about $7,000 per failure. This figure approximates our estimate of the average cost of external loads carried.

Four broad conclusions can be derived from these data:

1. Carrying external loads did not increase the accident rate of the CH-47 helicopter over its average rate for all other functions it performed in Vietnam. In fact, the accident rate while carrying external cargo was only about one-half that which the CH-47 experienced in all other usage.

2. The infrequent accidents that did occur, however, about doubled the costs of failures associated with carrying external cargo, because of extensive damage to the very valuable helicopter.

3. Single unsupported, strapped-together, and net loads had the highest accident rates (for the single unsupported and strapped-together loads, predominantly while delivering).

4. Accident rates while delivering (landing) are, on the average, three times those experienced in either pickup or cruise flight.

D. ANALYSIS OF PREDOMINANT CAUSES OF FAILURES

General aircraft accidents are typically caused by complex and often obscure series of mechanical failures and human errors. Helicopter external cargo system failures conversely have relatively simple causes. We estimate that approximately 85% of the 371 failures we investigated were caused by fairly specific and isolated mechanical failures or human errors. This is not to say, however, that sorting out human errors from mechanical failures in external cargo system failures is not difficult and subject to great uncertainties. Nevertheless, while general aircraft accidents are often complex in the immediate ways in which they occurred, external cargo system failures tend to become complex only when one considers the underlying reasons for their occurrence.

1. Pilot Error

For the purpose of this study pilot error is taken to be any failure not initiated by a mechanical failure and not specifically attributable to the air or ground crewmen. This error is a many-faceted variable, but for the purpose of our analysis, only two components of this error are of significant importance: (a) inadvertent hook release, and (b) flying/load stabilization errors.

a. Inadvertent Hook Release

The hook release system for the various helicopters was described in Chapter IV–B.1. Basically, the pilots have electrical (normal) hook-release push buttons on their collective control sticks, and the air crewman has a similar control on his pendant pistol grips. The normal release system is inactivated by the pilot when the helicopter is in flight. There is also a mechanical emergency release system (that cannot be inactivated) that the pilot operates with a floor pedal and the air crewman by pulling a lanyard attached directly to the hook.

The rapid emergency-release requirements of the system tend to preclude consideration of safer but operationally slower design alternatives. No pilot can afford to be burdened with compounded release functions. When a real emergency occurs, the load must be jettisoned immediately to save the helicopter and crew. The least that should be expected of the activation mechanism is that it require a distinct, purposeful manipulation that is not easily confused with other functions. Moreover, it should not be possible to activate it easily while performing other manipulations. In the end it comes down to one or more members of the air crew having immediate provision and responsibility for releasing the load. This responsibility, of course, can be – and obviously is – sometimes misused. Inadvertent hook openings frequently occur when inexperienced and relatively tense pilots are involved.

The hook-activation control switch in the Boeing-Vertol CH-47 appears to fall short of the aforementioned requirements. We assume that the CH-46 controls are similar. If a pilot grips the collective control on which the switch is mounted too low – and there is little to impede such a move – he can easily activate the hook. The Sikorsky CH-54 control conversely requires a distinct crossover thumb motion to activate. The control handle is also shaped in a way to prevent switch activation by the hand sliding up too high and accidentally activating it.

Several commercial operators interviewed claimed that the release switch need not and probably should not be on the collective control stick at all. They maintained that it should be taken off and put on the instrument panel.

Whatever the optimal solution is, it is fairly obvious that the human factors design of this control needs some redesign, particularly in the Boeing-Vertol helicopters. Loads are currently lost needlessly because air crewmen sometimes grow tense or inattentive. The controls appear to be too accessible and too easily confused with several others on the same stick or pistol grip.

b. Flying/Load Stabilization Errors

Load-stabilization problems, particularly for the predominant single-point slinging method, occur in a significant percentage of total loads carried. They happen to both experienced and inexperienced pilots. However, experience is

extremely important in preventing such problems from becoming failures. Commercial operators cited load stabilization as one of their principal problem areas. Fifteen percent of the 371 military failures analyzed involved load-stabilization problems. Thus, it is apparent that such problems are also serious in the military.

Outside of a very few loads of well defined geometry, no one can practically and comprehensively, before the fact, predict how a given load will fly. There are too many variables. Current practice calls for an initial gingerly low-speed flight to observe how the load flies, and then setting it down for rigging readjustment if problems are apparent. Nevertheless, loads often go instable in flight, and it can be difficult to compensate for these instabilities. For example, if a load starts a fore-and-aft swing, the pilot must make control compensations that are 180 degrees out of phase with the load, and the helicopter responds too slowly to make what might first be considered normal corrections. An incorrect response by the pilot will force the oscillations still higher – frequently to the danger point. In such cases no pilot can be faulted too greatly for jettisoning a load worth $5000 when it endangers his crew and $2,000,000 helicopter.

Aerodynamically most loads are complex. They are typically comprised of segments that have differing aerodynamic qualities, for instance, a truck or a load of items in a net. The drags that the individual segments of these loads induce in flight are markedly different from one another, and they may create a turning moment on the load in flight. In addition, relatively flat surfaces will induce positive or negative lift. Usually many flat surfaces are present – lifts and moments add and substract in a great many complex ways.

If the center of drag is spaced well behind the center of gravity, the load will be rotationally stable in flight, an example being a load with a drogue chute attached. However, even this type of load may not be stable from fore-and-aft and lateral oscillations, which can be generated by varying drag forces that can have several origins.

The drag on a load can be expressed as follows:

$$D = f(C_d V^2 S)$$

where C_d is the coefficient of drag which is dependent on the shape of the load, V is the velocity, and S is the projected area.

It can be seen that drag is very sensitive to changes in velocity. Changing velocity from 30 to 100 mph in the case of a nonaerodynamically shaped load (C_d is not a function of velocity) would change the drag by a factor of about 10:1. For an aerodynamic shape such as a cylinder, the C_d becomes a function of velocity, and thus drag, for the same parameters, would probably only change by

a factor of 4:1. From the foregoing it can be seen why decreasing speed is the classical first step in correcting for load-stabilization problems.

Load drag does not have quite the static effect on rigging stress as the drag equation might suggest. The drag is a horizontal force, while the rigging is close to vertical. If one flew a load fast enough so that the drag forces equalled the static weight of the load, the rigging-to-load centerline would fly at approximately 45 degrees (very unlikely except for very low-density loads). While the helicopter itself might have to add considerable power to compensate for this drag, the stress on the rigging would increase only by a factor of 1.4:1. At a more normal drag angle of 30 degrees, the stress in the rigging would be only 15% over the static stress due to the load itself.

A more significant problem is load drag as it relates to the generation of high dynamic stresses in the rigging. Changes in the magnitude of load drag may cause the load to swing, while changes in the center of drag may cause the load to rotate. The initiating forces are generated by turbulence and maneuvering. In the most severe instances, variations of the projected shape of the load in the air stream force the oscillations to ever-increasing amplitudes. If the load swings to 75 degrees from the vertical, the rigging stress at the peak of swing would be about 3.9 times the static stress. Rotational dynamic stresses which peak when the slings wind up can be equally great.

Another and fairly catastrophic load-stabilization problem deals with collective vertical bounce. In this case, which chiefly occurs with dense loads during takeoff and landing, the load bounces on the rigging in tune with the rotor but 180 degrees out of phase with the helicopter. It is a function of rigging-elasticity/load-weight combinations that have a natural frequency that can be forced by the rotor frequency. Collective vertical-bounce effects on the helicopter are extremely violent. The pilot can scarcely maintain control. The G forces become tremendous, and thus the only practical solution is to jettison the load.

Rotational forms of load instability, if there is not a swivel, are also generally beyond the pilot's capability to correct. Once a load starts really rotating continuously in a fixed direction, about the only solution is to get it back on the ground or to jettison it. Mild rotation of less than a complete revolution is fairly normal but continuous high-speed rotation will wind up the slings and, almost without exception, fracture them at the hook.

Swinging-type load instabilities are generally correctable by the pilot. Slowing down is typically the first maneuver. If slowing down does not stop the swinging, usually turns are executed. A properly executed turn will throw the load out into a different trajectory where the helicopter can "chase it down" and dampen the swing.

The pilot is severely hampered in these corrective actions, however, because in most cargo helicopters he cannot see the load. He can immediately "feel" these low-frequency oscillations because they are rather closely coupled to the helicopter. If somehow the load were magically suspended out in front of him (this could be done with TV perhaps), he would have a much better sense of when and where to maneuver. As things stand now, the pilot must first sense the frequency of oscillation and then make 180-degree out-of-phase control compensations of the same frequency. The oscillations can become quite serious before he can accomplish all this maneuvering, however.

Swinging-load instability corrections are made more difficult and vertical-bounce effects are often amplified by pilot-induced control efforts. When instabilities occur, it is not just the load that becomes unstable – the pilot becomes unstable as well. This results in a flight profile in which the pilot is bouncing in his seat attempting to correct the driving force – the load – that is oscillating at the end of the rigging. As a servo system, it is very poorly coupled.

One corrective action that is taken to alleviate some such poor coupling is to increase the force required to manipulate the collective control. These controls have an adjustable friction-brake mechanism that allows the pilot to make this adjustment. With the collective control force adjusted to high levels, the pilot can do a good deal of bouncing around in his seat without exercising much of any control. However, this procedure, while it is obviously beneficial, leaves many questions. Basically, the helicopter does not maneuver at all until the control is pushed with enough force to move it. At that moment when the control is pushed hard enough, the pilot, helicopter, and load are again closely coupled.

2. Sling Failures

Nylon sling failures constituted one of the two largest categories of failures in the external cargo-handling system studied. On the average for the four helicopters studied, they accounted for 24% of the total failures. Sling design is now the subject of extensive research by the Eustis Directorate and other agencies. Because of this excellent ongoing work, we shall refrain from treating the subject too exhaustively here.

Since approximately 77% of all the sling failures studied occurred in cruise flight, it may be deduced from the rather moderate additional dynamic loading which occurred statically in this phase of flight that either (a) slings have been stressed to very near their ultimate strength or (b) a great many load-stabilization problems with concurrent high stresses occur in flight. Probably both occurrences are significant.

As one might expect, slings tend to fail at their junctions with other hardware where stress concentrations occur, and sewn lap joints always have less

strength than the nascent webbing. Sling designs and rigging practices which were relatively static until 1965 (air drop and ground rigging materials used) have just begun to show an appreciation of both these effects.

Perhaps the greatest stress concentrations may be found in a choker hitch knot sometimes used with the universal cargo sling set.* One might expect stress concentrations in portions of this knot in a web sling to be 5 to 10 times greater than the stress in the body material. Although the manual recommends that the chocker hitch knot be used for loads exceeding 500 pounds per sling leg, under combat conditions it was inevitable that the choker hitch was used for heavier loads in desperation or by mistake, since these slings did not have chain legs or other means of attachment.

An extremely common example of a stress concentration is the multilegged sling in which each leg is looped through a multi-plied nylon doughnut. Even the currently popular nylon chain leg cargo sling (FSN1670-902-3080) is of this construction. When loaded, the sling loops slide together and buckle transversely. Stress concentrations are estimated to be at least 3 to 1 at these loops inside the doughnut.

Undoubtedly stress concentrations also occur in the plied doughnut. However, another failure mechanism is of greater concern there and perhaps also even in the slings themselves. This is the effect of abrasive friction, which can generate temperatures high enough sometimes to melt these nylon components. Almost certainly abrasion can generate temperatures high enough to cause elongation and strength degradation. The Army Quartermaster Corps Laboratories at Natick, Mass., have told us that they have examined slings and doughnuts which had been almost completely melted after failure. They feel that plied construction of slings and doughnuts should be avoided and that more thought should be given to abrasion attenuation and heat dissipation. They feel that these goals can be accomplished by avoiding plied materials and using the proper fabric-to-metal interfaces.

Slings used in Vietnam in the period studied employed factors of safety that are a fraction of those recently recommended by a number of agencies. Factors of safety of 3 to 1 or 4 to 1 were common. In July 1972, the Eustis Directorate published a design guide for slings (Technical Report 72-36) reflecting the newer thinking for factors of safety and other sling-design factors. It recommends factors of safety in excess of 11 to 1, which is in line with factors of safety employed in nylon cords for automobile tires and other long-life nylon applications. As the higher factors of safety are put into effect, sling failures should be reduced considerably.

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*As shown in Figure 4-2 in TM 55-450-8.

To avoid the unequal stress in sling legs inherent in previous designs, the design guide recommends the use of slings whose lengths can be adjusted by a chain leg end or a webbing gripper. Textile-webbed sling legs whose ends are formed into a loop over a pin are required to have a wear pad sewn on the inside of the loop to prevent abrasion where it passes over the pin. The pin is required to be of 1-1/4-inch diameter, or larger, so that no significant strength loss is incurred due to stress concentrations.

The report recommends that nylon slings be shielded from the sun when not in use to prevent ultraviolet degradation of the material. Coating of the sling material with urethane or polymers is required to prevent sand from being worked into the weave and causing material damage. This latter requirement may be harder to accomplish than to specify, especially since the Army Quartermaster Corps Laboratories at Natick have been attempting to do this for years without notable success.

3. Hook Failures

Hook failures accounted for 12.8% of the 371 total failures analyzed. However, hook failures are difficult to differentiate from human errors of the air crew, such as inadvertent hook release. Air crewmen, quite naturally, are reluctant to log accidental drops if there is any reasonable possibility of other causes. In fact, because of relatively poor human factors design of hook release switches (particularly in the CH-46 and CH-47), they may often be unaware of an inadvertent activation. This would be particularly true of incidents occurring under stressful conditions.

We have taken hook failures exactly as they were reported. Therefore, for the above reasons they may appear to be somewhat overstated, but we believe not seriously so. For one thing, they happen more frequently in flight on the average than during pickup or delivery (one would not expect inadvertent activation in flight). For another, we have reviewed field maintenance correspondence which pinpoints many serious and unresolved problems with current hooks.

The hook is the apex of the external cargo-carrying system. Where nets, straps, and many other mechanical components may partially fail and still not cause the system to fail totally, the hook conversely must function near perfectly. It is the intractable nature of its function that makes the hook doubly important – the whole mechanical system is suspended from it.

Current hooks, particularly the electromechanical variety, experience many problems, which stem from the specified requirement for light weight, rapid but remote activation, and a number of other geometrical constraints. They generally are specified as having to release at least one-third of their rated load capacity in

about one-half second. But as a practical matter, the manufacturers, at least in recent years, have designed them with the capability of releasing the fully rated load.

The mechanical (emergency) releases are generally specified as having to release about three times their rated load, which is also the ultimate strength of the hook. They typically give the manufacturer the option of calling for the hook to be rebuilt if anything over the rated load is released. To achieve all these characteristics, current hook designs often have latching mechanisms with relatively marginal characteristics. To save power, size, and weight in the activating solenoid, in the past at least they have resorted to extremely small latching overlaps (on the order of 0.010 inch). These rather closely toleranced latches were subject to work-hardening degradation and they often vibrated open under load. In the words of many pilots: "They had a 'hair trigger'." Substitution of fabric doughnuts rather than clevises to attach the load slings to the hook was effected to help alleviate this particular problem in some helicopters (particularly the CH-47). Increasing the latching distance is a recent change that has also increased hook reliability.

A significant problem with the electromechanical hooks is that they will not always completely relatch after activation. In some instances the emergency release cable has restrained full relatching. Personnel learned that manual closing from a full-open position was necessary to ensure that these hooks were fully latched.

The hydraulic/pneumatic hooks of Boeing-Vertol differ markedly from the electromechanical variety. In this hook the load beam is activated by a cam that is driven by a prepressurized pneumatic cylinder in series with a hydraulic cylinder. Normal activation is effected by the hydraulic cylinder, which is controlled by a solenoid valve via a relay using the normal release switch on the collective control. The emergency activation of the hook is accomplished by releasing the pneumatic charge manually via a mechanical lanyard-operated release valve. This type of hook is slower in operation than the electromechanical hook, requiring about 3 seconds to open. However, the control functions, as far as we can see, are identical to those of the electromechanical hook. From our data analysis, there is not much to suggest that the failure rates of this hook are higher than those of the electromechanical hook or that the slowness of its operation effects human error, or causes other mechanical failures.

The mechanical (emergency) release on all hooks consists of a mechanically operated cable that activates either a latch in the electromechanical hooks or a valve in the hydraulic/pneumatic hooks. A relatively common problem leading to failures on the CH-46 and CH-47 was incorrect installation of these cables. They were frequently installed with insufficient cable length so that lateral movement of the hook in flight on its track would activate the emergency release.

Spurious activation of the hook opening relay by electrical transients is another problem. This is not a well documented phenomenon, but many air crewmen interviewed feel certain that it happens.

We feel that there are a number of things in the data suggesting that hook reliability designs could and should be improved. However, the good and bad features of current hook design are currently pretty well locked into military specifications, where their geometry, operating principles, and parameters are all pretty rigidly spelled out. Currently there probably is not sufficient motivation for someone to attempt a totally different design – the market is relatively small.

We feel that the Boeing-Vertol hydraulic/penumatic hook is basically more rugged and reliable in principle than the electromechanical principle of other hooks. However, Boeing-Vertol's human factors design of the hook control functions is currently less effective than Sikorsky's, which utilizes the electromechanical principle.

What is needed is a systematic requirements study, possibly followed by an investigation of totally new design approaches. The requirements study would have to take into account applications such as the CH-54 and projected HLH hooks that are not fixed to the helicopter but to a winch cable. It should pin down just the critical major requirements without precluding a "blue sky" redesign approach.

4. Strap Failures

Straps are components that hold together a load (as in strapped-together loads) or otherwise retain a load (as in strapped-down rotors in downed helicopter recoveries). Straps differ from slings in that they are never directly attached to the hook to support the load. Their support functions are indirect.

Strap failures accounted for 6.5% of the total failures analyzed. Straps are, of course, very simple components. Their failures are almost uniquely associated with two types of loads:

a. Disabled aircraft recoveries,

b. Strapped-together loads.

Straps typically are not used with other types of loads.

In aircraft recoveries, straps are used to tie down the rotors on helicopters or to provide attachment provisions for the slings (belly bands). Failures of straps

thus employed are frequently caused by misapplication (human error) rather than by mechanical failure. Strap failures and pilot error are the two largest causes of failures involving aircraft recoveries. The two causes of failures are very nearly equal in magnitude, and their sum accounts for about 75% of all of these failures. Since dropped aircraft account for the overwhelming majority of the value of all loads dropped, failures of – or attributed to – the lowly strap are very costly.

In strapped-together loads, a number of items are made into a coherent whole by the various items being strapped together. Since helicopters seldom land or take off without skidding the load to some degree, straps in this application are often seriously abraded. Straps so abraded tend to fail when subjected to the increased stresses of cruise flight.

Another common cause of strap failures in strapped-together loads does not actually involve mechanical failure of the straps at all. These failures occur when straps fail to constrain elements of a load in flight. In loads of strapped-together telephone poles, for instance, it is common for a pole to slip back through the straps and drop from the load. If the straps themselves are not constrained properly in position with spreaders, the sling forces may move them together to the point where the load is lost. Both these instances might have been counted as strap failure where, in reality, they were probably caused by human error.

In summation, strap failures are often caused by or confused with human error. However, one can postulate that more abrasion-resistant straps with more foolproof clasps would possibly be very valuable.

5. Net Failures

Net failures accounted for 6.9% of all the failures analyzed. The incidence of net failures increased slightly in cruise flight over those during pickup. The incidence while delivering was less than one-half that experienced in either pickup or cruise flight.

Nets like the straps in strapped-together loads tend to become abraded while the helicopter is picking up or landing. The data suggest that these abrasions are frequently severe enough to cause on-the-spot failures.

A mitigating factor seems to be that nets were frequently used to carry loads in excess of their rated capacity. Net failures predominated as the cause of failure involving high-density loads, accounting for very nearly 50% of the failures of high-density loads in the CH-47 helicopter. Conversely, net failures were nearly non-existent with low-density loads and very moderate with medium-density loads.

The evidence seems to indicate that the Army overwhelmingly preferred nets to containers. We postulate that this was because of the greater utility and mobility of nets over containers. We further suppose that this led to the routine use of overloaded nets because their greater utility counterbalanced their relatively high failure rates. Additionally, net loads tended to have relatively low value, which made failures less critical.

6. Pilot/Air Crew Errors

Pilot/air crew errors are characterized by breakdowns in communication and guidance. In most helicopters analyzed, the pilot can see neither the load nor the rear sections of the helicopter, and he must utilize air crewmen for required guidance. However, he has learned that the ground crewmen are unreliable in this function. The air crewman guides the pilot over the load, tells him when it is connected and disconnected, and warns him of possible collisions of, say, the tail rotor with obstructions. Breakdowns in the communication link between the pilot and air crewman frequently lead to failures, principally collisions with trees or cargo.

Some 6.2% of all the failures analyzed were attributable to pilot/air crew error. No more definite information on the nature of this cause of failure was obtained in our analysis. In other words, these failures did not seem to increase with any particular category of load or load density. Neither were they greater during pickup than delivery.

However, reading actual accident reports suggests that this is one cause of failure that might be easily reduced. They lead one to believe that current communication links are often weak among the air crew and nonexistent with the ground crew. Strengthening these links should not be difficult. The evidence is that commercial operators have done just this with substantial benefit.

7. Ground Crew Errors

If one counts ground crew errors as just those failures that occur because of rigging misapplication, they rank about 7th after pilot/air crew guidance errors. Because of the severe problems associated with analyzing these failures beyond this point, they were so considered in this study.

Of course, there are many other ground crew errors that are not illuminated by this method of analysis. If one could assess the frequency of ground crews using obviously deteriorated rigging materials, or misapplying these materials in ways that cause them to fail, ground crew errors would be substantially higher. It is even conceivable that these errors could be the largest single cause of failures. For this reason their analysis is extremely important to the study, although a highly quantitative assessment is not possible.

As far as we have been able to determine, ground crew errors in Vietnam were overwhelmingly due to training inadequacies. Few ground units had any formal training in rigging for external airlifting. Most training was left to the discretion of individual unit commanders. Some felt it was important and pursued it; others did not. Practically every air crewman interviewed cited a very great variability in the reliability of rigging applied by various ground units. With loads rigged by some ground units, failures were extremely rare. With others, failure rates were extremely high. Many air crews cited examples of their training deficient ground units after which their work became completely acceptable.

One theory holds that ground troops are relatively incapable of properly maintaining rigging materials in the unprotected and hostile environment in which they function. This theory appears to be only partially true. Everything in the field need not be left in the mud, even though mud is a way of life there. While, for instance, nets were obviously sometimes left stored in the open and/or run over by vehicles from some units, they could have almost as easily been protected from both these degrading actions – and they obviously were by the better trained units. Ammunition boxes are almost universally and abundantly available to ground troops for storage. It is almost as easy to store materials in an ammunition box as to throw them on the ground. There is a tolerance to deprivation about field operations, but this does not translate 1:1 to a tolerance of equipment abuse. The ground crewman is typically concerned about his battalion's equipment – his life may depend on it. Therefore, it can be assumed, we think, that ground troops are highly motivated not to lose cargo. A battalion does not want to drop its own equipment or supplies – replacements may not be readily obtainable.

A review of training and other manuals and stock lists is enlightening. It shows, in our opinion, that the ground crewman currently does not really have the comprehensive and current information he needs to do his job properly. Moreover, the amount of information he needs is not very great. Minimally it should include:

- What rigging materials are available to him from the company depot (stock numbers, photographs, etc.);
- Generic descriptions of what and how they are applied;
- Storage, cleaning, and inspection criteria;
- Emergency instructions – what other materials and configurations can be used for rigging in emergencies (proper material unavailable).

Current applicable training manuals, we feel, suffer from three marked deficiencies: (a) they are far from comprehensive (they half-treat the subject); (b) they are not current, even appearing to have been significantly obsolete when published (the subject is developing too fast for current publication prodecures); and (c) the subject is treated too specifically (e.g., how to rig eight nested half pontoons). This leaves the uninitiated reader with the erroneous impression that each rigging job is unique and the subject complex.

The ground crewman needs two things that he is not currently uniformly getting to make him a reliable rigger: (a) better training and (b) better manuals.

A second, completely different area of inadequacy of ground crew performance is ground crew/air crew communications. Pilots treat ground crew hand signaling almost as a joke – and it probably is. Minimally it is held in such disdain by pilots that it has to be ineffective.

Pilots say they often cannot tell which of a number of ground crewmen waving their hands is supposed to be directing them; or if a ground chief is obvious, he is stationed in the wrong place and he cannot adequately be kept in sight, or he may attempt to direct the pilot down or crosswind. The pilot is in radio contact with a radioman on the ground, but this link to the ground crew chief is too remote to be effective. All this says that the communication link should be direct and two-way.

Commercial operators, who function much more precisely than the military (i.e., ski lift bolt holes placed over the bolt, etc.), use direct-to-the-riggers voice communication exclusively. Voice communication in the military would similarly also allow the pilot to effectively ask the ground crew a few pertinent questions, such as, "Do I see a rip in the side of the net" or "I can't move crosswind near that stack of materials."

The pilot needs to be in direct contact with the ground crew chief. The military, we believe, has to develop direct voice communication systems.

E. COST/VALUE OF CARGO DROPPED

In Sections A and B we looked at data dealing with failure occurrences and failure rates. These data identified the high failure rates experienced during cruise flight of high-density loads in general, and strapped-together loads, disabled aircraft, and net loads in particular. The value/cost of the materials in a particular load category, as well as the failure rate associated with that category, constitutes major system cost-effectiveness parameters. These parameters also identify monetary losses that might be alternatively applied to improving the system.

Replacement cost and value may be two entirely different things, particularly in combat. For instance, a low-cost resupply load of ammunition to a beleaguered battalion may be of inestimable value. The increment of value over cost where they are different is difficult to estimate but, all else being equal, would drive us to always opt substantially for alternatives having lower failure rates (fewer numbers of losses).

Table XVI shows the results of our endeavor to develop the replacement cost of loads lost by the CH-47 in 1968 and 1969. The basic load categories, distributions, and failure rates are derived from data which were previously developed in Sections A and B.

Estimating average costs per category was difficult to do precisely. However, we had enough bench marks to make the process fairly realistic. For load category 1 – disabled aircraft – we learned that these aircraft had an original procurement cost ranging from about $59/pound for the UH-1 to $122/pound for the low-production CH-54. The CH-47 models A/B cost on the order of $55/pound, but by the C model inflation and other factors, the cost of the CH-47 was driven to about $100/pound. The aircraft that were carried as loads by the CH-47 were predominately UH-1's and Cobra's, small two-seater helicopters and some fixed-wing aircraft. An estimate of an average replacement cost of $60/pound seems realistic.

Single unsupported loads (Category 2) are principally vehicles, but also include some electronic equipment and the like. Vehicles in large-scale production, like jeeps and small trucks, will cost approximately $1/pound. More specialized low-production vehicles will cost $2 to $3/pound, and electronic equipment may cost $5 to $20/pound. All things taken into consideration, a cost of $2/pound seems realistic for this type of load.

Categories 3, 4, and 5 (containers, pallets, and nets) tend to contain the same materials. Much of these loads consist of foodstuffs valued at less than $1/pound. Others consist of ammunition, medical supplies, spare parts, and the like. Ammunition costs around $2/pound. Some pharmaceuticals are very costly, but a realistic average for all these materials in these categories of loads, we feel, would be about $1.50/pound.

Finally, strapped-together loads consist mostly of lumber, pierced-steel planking (PSP), telephone poles, and the like, and we estimate their value to be about $1/pound.

These values are arrayed in their respective load categories in Table XVI. We then proceeded to calculate the weights and costs of materials lost in each category by external cargo system failures. We did this by multiplying the 1.35 million tons of external cargo known to be carried in the period by the percentage of load in each category, its failure rate, and the average replacement cost per pound.

TABLE XVI

COSTS OF EXTERNAL LOADS DROPPED BY THE CH-47 HELICOPTER IN VIETNAM IN 1968 AND 1969

Load Category	Description	Load Distribution (percent)	Failure Rate ($x10^{-3}$)	Average Replacement Cost ($/lb)	Weight of Cargo[1] Dropped (lb) *	Cost of Cargo Dropped (million $)	% of Total Value
1	Disabled Aircraft	7.3	4.54	60	894,834	53.69	88.6
2	Single Unsupported	28.8	1.89	2	1,496,664	2.99	4.9
3	Containers	11.7	0.405	1.50	127,940	0.19	0.3
4	Pallets	14.1	0.336	1.50	127,915	0.19	0.3
5	Nets	32.7	2.54	1.50	2,242,566	3.36	5.6
6	Strapped	5.8	9.4	1	147,204	0.15	0.2
Total or Distributed Av.		100.4	2.35	5.89	5,037,123	60.57	99.9
Average Per Month					209,880	2.52	

* Based on 1.8 million tons of cargo carried in the period and 75% or 1.35 million tons carried externally.

We arrived at $60.57 million worth of failure-associated cargo in the two-year period. These failures – overwhelmingly – were dropped loads. Thus in the peak 1968 and 1969 period in Vietnam, the CH-57 helicopter dropped more than $30 million worth of cargo each year. The CH-47 was carrying approximately 81% of the external cargo carried there at the time.

The constitution of the loads dropped is perhaps of even greater interest. Almost 89 percent of the replacement costs of these loads was disabled aircraft. This load category amounted to some $35 million worth of cargo per year alone. If one assumed generously that salvage was 50% of the new replacement value of loads dropped, this would mean that the Army was losing the equivalent of 9 new CH-47-D's or CH-54-A's or about 45 new UH-1's a year.

The number of disabled aircraft loads on which these failures are based seemed high, so we double-checked. We first questioned the 7.3% distribution which was arrived at from consensus data of CH-47 pilots and air crewmen. This is an awful lot of aircraft carried, about 32,000 over the course of the total Vietnam conflict. We knew, for instance, that the CH-47 had made only 10,900 recoveries of downed aircraft up to mid-1971. We also knew that by mid-1969 only 5,656 aircraft, including 2,878 helicopters, had crashed in Vietnam. There appeared to be a large discrepancy in the data. However, further conversations with pilots convinced us that most of these loads were aircraft carried for maintenance purposes, not recoveries. Recoveries then appear to represent only about one-third of these loads, which means that on the average these loads have relatively high value (they are not extensively damaged). For all these reasons, the importance of improving the reliability of carrying aircraft loads becomes extremely critical.

F. PROJECTIONS FOR THE HEAVY-LIFT HELICOPTER (HLH)

One of the prime objectives of this study was to extrapolate current system findings to identify potential problem areas in future heavy-lift systems. Plans for the HLH call for it to fly heavy loads at normal cruise speeds (current helicopters typically fly external loads at about one-half normal cruise speed). HLH load categories will be either single-unsupported or containerized and will weigh up to 22-1/2 tons.

Our findings show that flying dense external loads at high speeds could very well result in extremely high failure rates. However, these findings relate only to past experience with various types of single-point suspension loads employing current rigging materials. The HLH experience of the early 1980's will be gained with loads restricted to two relatively low failure rate categories and flown with multi-point suspensions with vastly improved rigging materials.

Thus, on the one hand we perceiv a set of parameters that could lead to high failure rates mitigated by projected materials developments in the system. However, in three areas having high probability of causing significant failures – pilot error, hook problems, and inadequate rigging by ground troops – we cannot see appropriate ongoing remedial developments.

We found that the CH-54, which functions more like an HLH than any other current helicopter, had two causes of failures – pilot error and hook failures – that stood out from the experience of other helicopters.

When one attempts to maximize the external payload utilization of a helicopter, failure rates increase markedly, but this is really one of the principal goals behind the HLH development, viz., to increase the payload utilization of cargo helicopters, while at the same time reducing costs. To realize this goal, every part of the system will become critical. Heavily loaded helicopters experience increased difficulties in taking off and landing. Heavy load instabilities in flight have a much greater effect on overall helicopter stability than lighter loads. It is also true of almost any mechanical tool that, when you attempt to maximize its work output to levels very close to its potential, the reliability of each component part of that tool becomes critical.

Of greatest concern is pilot error. The pilot will undoubtedly need more sophisticated mechanical flight control assistance in flying very heavy external loads than has been the case in the past. This concern and possible remedial developments are covered in Section D-1.

Secondly, we are concerned about hook design. When we speak of hooks, we do so in the larger sense, encompassing controls, cabling, electrical commutation, emergency provisions, and the basic function of the hook itself. Our concerns about hooks are developed in Section D-3.

Thirdly, we feel that very probably there are also desirable changes in the basic system employed in external cargo carriage. We refer to the practice of rigging procedures and materials being left almost totally in the hands of ground troops. It is easy to see that deficiencies in this area will be compounded as loads become heavier. The system results in the pilot lifting an unknown quantity in terms of the integrity and application of rigging. Risk is increased over loads rigged by air crews, and failures jeopardize the helicopter. These issues particularly concern the people involved with the HLH development, but are largely unresolved at this time.

Clearly the pilot and/or air crew cannot supervise or even inspect the rigging of most loads. To do so would seriously compromise the utility of the helicopter. It is also clear that ground troops in the current system cannot be depended on to always have the proper rigging materials and/or the knowledge to correctly apply them.

Some well informed persons feel that each piece of equipment ought to have built-in airlift rigging materials (wind-up slings in little boxes at the corners). Others feel that all rigging materials ought to somehow be placed in the hands of the air crews to be inspected and dropped just before use at a pickup zone.

While integrated HLH design is well under way, it appears that the remainder of its external lift system – the load attachment and rigging subsystems – is being undertaken in a fairly unintegrated fashion.

Therefore, it is our opinion that HLH failures may be high unless additional attention is given to three areas:

1. Pilot error/external-load flight control,
2. Hook design, and
3. Changes in rigging practices.

VI. CANDIDATE CORRECTIVE ACTIONS

A. FAILURE CAUSE RANKING

Our ranking of the most significant causes of external cargo-carrying system failures, from greatest to least, follows:

1. Sling failures,
2. Pilot errors,
3. Net failures,
4. Strap failures, and
5. Hook failures.

A substantial amount of research and development is currently being directed toward the development of more reliable rigging materials, including slings, straps, and pendants. From results to date, one can realistically project an early and dramatic increase in the reliability of these components. Therefore, we do not perceive that they are sensible candidates for corrective action under this contract. Such corrective actions are being successfully carried forward under other auspices.

From the analysis of Chapter V, we showed that about 88% of the total replacement cost of all cargo dropped was attributable to dropped aircraft. Therefore, the unique requirement for carrying this category of load is very important.

If one then disqualifies rigging materials from further consideration and adds in aircraft transportation, a ranking of corrective actions, one of which we might realistically develop, becomes:

1. Aircraft recovery failures,
2. Pilot errors,
3. Net failures, and
4. Hook failures.

B. CANDIDATE AREAS

These are the candidate areas we wish to emphasize. We will hereafter discuss each candidate separately.

1. Aircraft Transportation Failures

Aircraft transportation failures are unique in three ways: (a) they account for an almost overwhelming majority of the cost of all failures, (b) they account for almost all the low-density load failures, and (c) they embrace a much higher proportion of human error than does any other load category.

The most prevalent mechanical cause of this type of failuure is that involving rotor tie-down straps on helicopters being transported. This is followed closely by pilot error, which consists of the load "just getting away" – flying or swinging up into the bottom of the helicopter, or threatening to do so.

While one can imagine many mechanical changes in the system that might reduce failures while transporting aircraft, it is hard to envision that these changes would effect a significant reliability improvement because human error predominates. Military aircraft should have sufficient hard points so they can be lifted by helicopters or cranes. Helicopters should have built-in rotor tie-downs or provision for locking the main drive transmission. However, the few deficiencies in these areas are known, and we assume they will be corrected shortly.

This leaves training as the principal remedial action required to attenuate aircraft transportation failures.

Our observations of the training procedures currently employed have been superficial. We have seen the training in CH-47's at Ft. Rucker and in CH-54's at Ft. Eustis. Our impression is that most of it consists of carrying concrete block loads. An old fixed-wing aircraft is also carried and a few other types of vehicles. We also noted that as little risk-taking as possible is inherent in the training procedure. Most of the training appears to be done on fairly flat and open ground.

Perhaps the answer to better training in this area is to introduce a lot more transportation of varied types of aircraft over much more varied terrain than is currently the case.

Another very good possibility is that an external load flight simulator be utilized in the training procedure. Such a simulator has been developed at United Aircraft, the parent corporation of Sikorsky. This simulator has been used to analyze rigging characteristics, but it seems very probable that such a simulator might also be invaluable in training pilots to fly external loads.

2. Pilot Errors

Pilot error, we think, may be substantially reducible. We have in mind a more sophisticated flight control system that, in addition to normal flight control augmentation for the pilot, would provide considerable assistance in flying external loads. Such a system should be especially beneficial in attenuating failures associated with transporting aircraft.

As we pointed out previously, pilots often fly a load too fast for its aerodynamic characteristics and/or the strength of the rigging. This is particularly true when pilots are inexperienced or under stress. The problem is compounded

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because the pilots cannot see the load and must fly and compensate for instabilities by feel. Flying by feel in all its perturbations requires extensive experience, and even then is not wholly to be trusted.

We understand that automatic external load/flight controls that memorize and automate the correct reactions to load "feel" compensations have been proposed in the past. We think that in the light of the evidence, this proposal makes eminently good sense.

All current helicopters are inherently unstable and require servo control systems to make them manageable in flight. It has been suggested that another input to this system should be the load drag angle. With such a system, the helicopter would fly at a somewhat variable but optimal speed which would maintain the same drag angle and rigging tension, while largely avoiding load instability.

Work is being done on a helicopter payload capability indicator of considerable promise at the Dynasciences Corp. Also, a stability and control augmentation system using optimal control theory has been investigated at Wright-Patterson Air Force Base. Perhaps these developments and the requirement suggest that the time has come to develop a unique external cargo helicopter stability, control, and instrumentation system with the following features:

- Maintaining a constant load drag angle (flying the helicopter optimally with an external load),
- Weighing and displaying the load weight, and
- Displaying the power margin for the load being carried for the altitude and temperature of that moment in the flight, considering the tare weight of the aircraft.

3. Net Failures

The practical utility of nets over containers to Army ground troops was apparent from the data. Undoubtedly they were repeatedly used over their rated capacity, frequently with attendant high failure rates. (They knew it was risky but did it anyway.) We assume that this was because nets are relatively easy to roll up, transport, and store – attributes not shared by containers or, to a lesser degree, even pallets.

The Navy has not experienced high failure rates with nets. However, they carry much lighter loads than the Army, which may be the answer. More probably, the answer is that they have developed a superior net with a built-in pallet.

The basic failure mechanism of nets is rupturing at the bottom. They are typically badly abraded during pickup and landing. A pallet in this bottom area fulfills two functions: (a) it absorbs abrasion in that area and (b) it prevents load compression and resultant load damage.

4. Hook Failures

Hook designs, in our estimation, need a whole new fresh look, possibly leading to a totally new design principle. Before this can happen, an analysis/testing program should be undertaken to answer some very basic questions. They are:

- How fast does the hook have to operate? Making it faster than need be either introduces intrinsic unreliabilities or increases its size and weight.

- What is the optimal geometry? Should it be a beam hook at all or should it, for instance, be a ball and socket with inherent swivel and rotation accommodations?

- What are the optimal normal control requirements? Where should the release switches be? What interlocks should there be? How should they interact?

- What is the optimal emergency release? This depends on first answering the first three questions.

VII. DEVELOPMENT OF SPECIFIC CORRECTIVE ACTIONS

After our analytical work, our study was continued in two areas: (a) net pallets and (b) cargo hooks. The Eustis Directorate instructed us to advance a specific concept for a new net pallet and to outline a program for investigating the design principles of cargo hooks. This chapter responds to this request.

A. A COLLAPSIBLE CARGO NET-PALLET CONCEPT

Current cargo nets when used to carry external loads have the following overriding characteristics:

Attributes	Inadequacies
1. Light, compact, and mobile; and	1. Exert high compressive and buckling forces on the load; and
2. Can be quickly loaded	2. Highly prone to abrasion-scrape damage.

As previously mentioned, the data suggest that their attributes significantly outweigh their inadequacies to the Army in the field. As a result, they appear to be used frequently, despite a relatively high failure rate, particularly when carrying the higher density loads. Therefore, a net that would overcome the current inadequacies of present-day cargo nets, while retaining most of their attributes, would become a highly valuable piece of field equipment. The criteria for such a net would include:

1. Fold to a very high packing density when not in use;

2. Component parts light enough for a maximum of two men to handle;

3. Fast, efficient loading functions;

4. Resistant to radial and buckling compressive forces when loaded and lifted;

5. Resistant to abrasion and scuffing damage when helicopter skids a loaded unit;

6. Loadable without equipment or personnel traversing over any of its component parts.

In addition, two other criteria would be extremely beneficial:

7. Capable of being transported when loaded with a forklift truck;

8. Rugged, damage-resistant, functional design.

Consideration of all these criteria forms the basis of the conceptual drawing presented as Figure 27. Interestingly enough, the conceptual net-pallet concept did not, in the end, involve a net at all. It consists of three components: (1) a pallet, (2) an eye rod, and (3) straps.

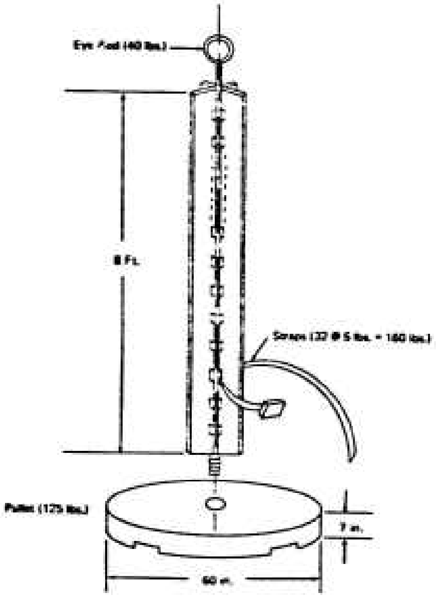
In use, the pallet would be placed on the ground and the eye rod inserted in its center. A suitable, reliable, quick-disconnect mechanism would be employed. A supply of straps either would already be attached to the eye rod or would be broken out in the immediate area. Items would be loaded onto the pallet by forklift, by truck hoist, or by hand. They would be strapped to the eye rod either singly or in groups as they are loaded, depending on their size. Straps employing quick-connect and disconnect features and ratchet tightening mechanisms would be used.

Even though up to 32 straps might be used, we estimate that the actual time required to install them would be less than 10 minutes. The time required to remove them would be much less, perhaps as little as 3 minutes.

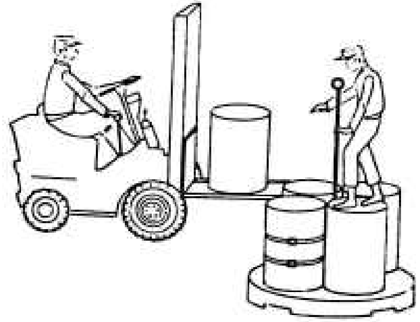
The pallet itself would probably be of lightweight, honeycomb construction. We estimate that it would weigh about 125 pounds and could easily be handled by two men. In our initial concept we chose a round configuration, since it could then be rolled. However, it could just as well be square or rectangular.

Disassembled for storage, the pallets could be stacked and the eye rods could be put in piles or hung on a rigid rod. Straps could be left on the rods if they were stored under cover.

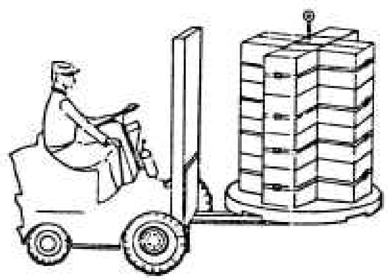
Each net-pallet could carry up to about 6,000 pounds and could be clustered as shown in Figure 27. To do this they touch. Pallets would have to be spaced so that they could assume moderately different and changing elevations in flight without interfering with one another. The most probable solution would be the use of spreaders as shown in the figure. These light, tubular elements would attach flexibly to the eye rods, space the loads, and resist resultant compressive forces.



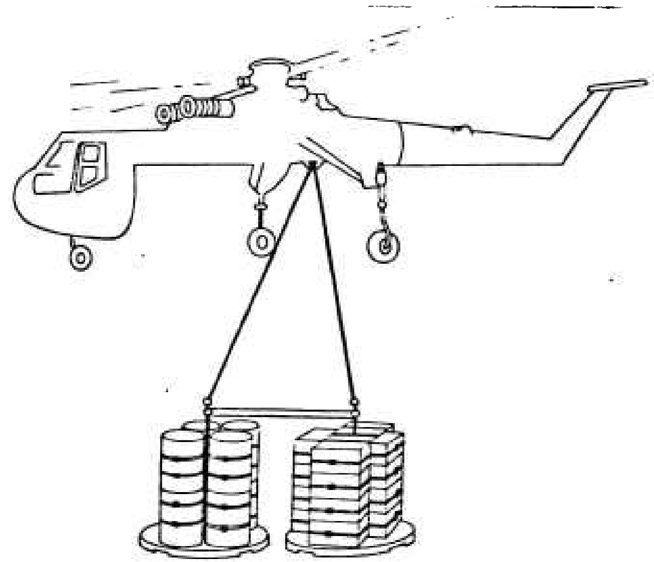
The proposed external cargo pallet



Loading with eight 55-gal. drums which will have a gross weight of about 4200 lbs.



Carrying a pallet loaded with forty 40-mm ammunition boxes – gross weight of about 5700 lbs.



Clustered pallet load weighing about 10,000 lbs.

FIGURE 27. CONCEPTUAL DRAWING OF COLLAPSIBLE CARGO NET-PALLET.

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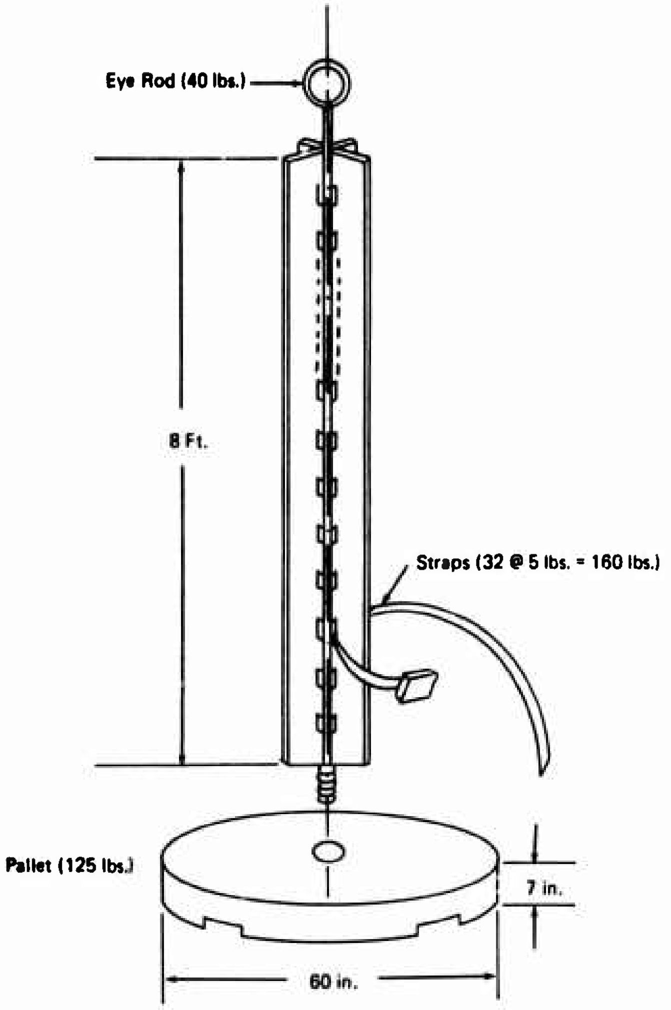

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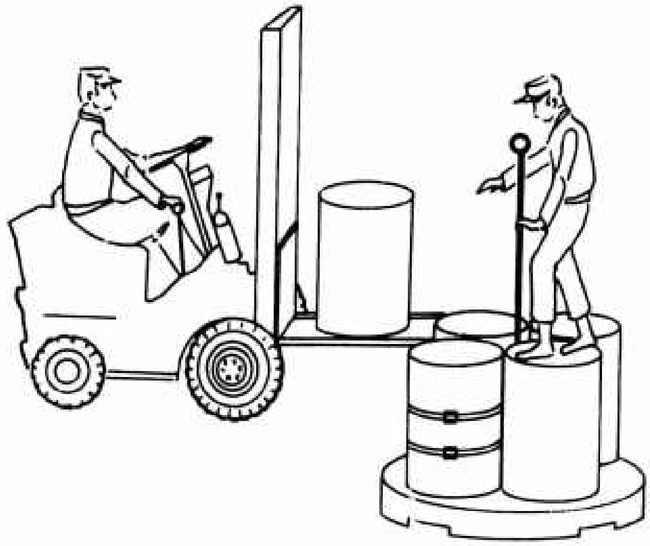

Loading with eight 55-gal. drums which will have a gross weight of about 4200 lbs.

Carrying a pallet loaded with forty 40-mm ammun boxes – gross weight of about 5700 lbs.

FIGURE 27. CONCEPTUAL DRAWING OF COLLAPSIBLE CARGO NET-PALLET.

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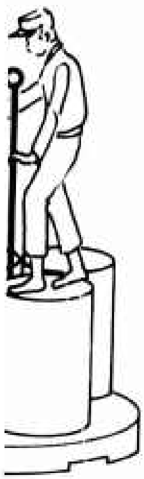
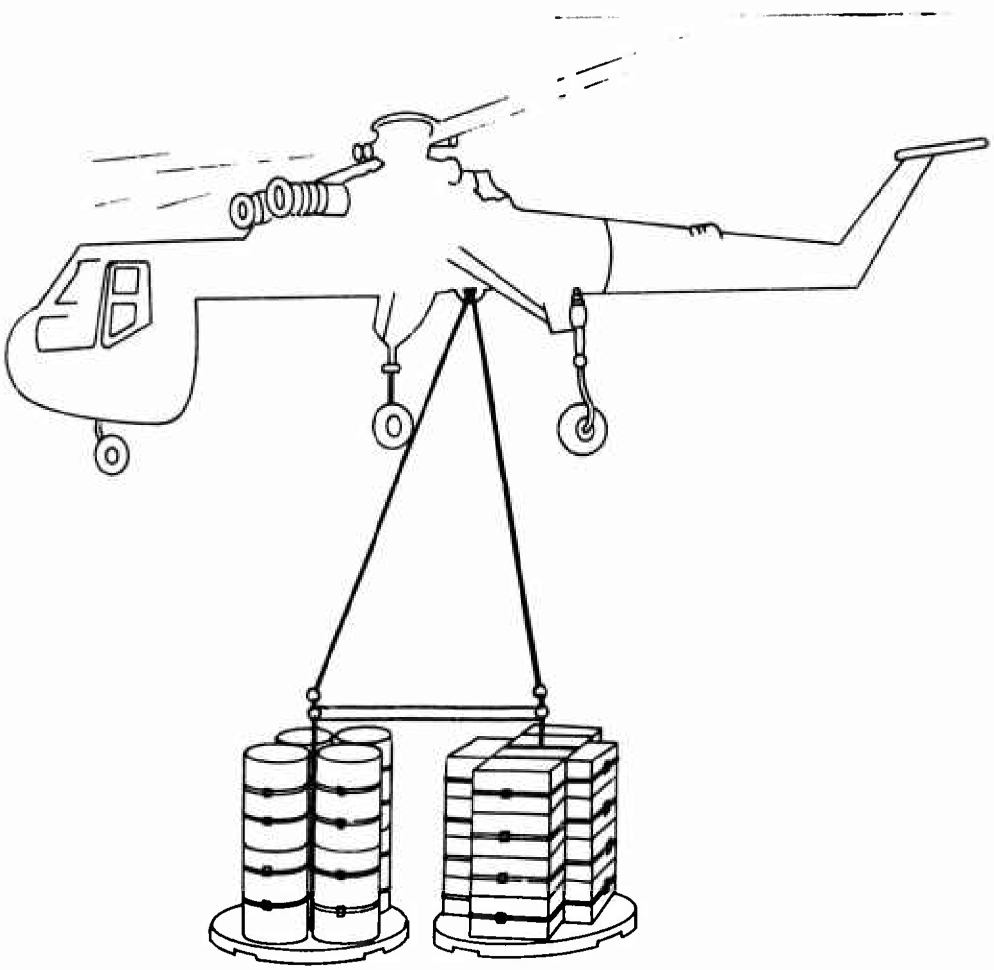
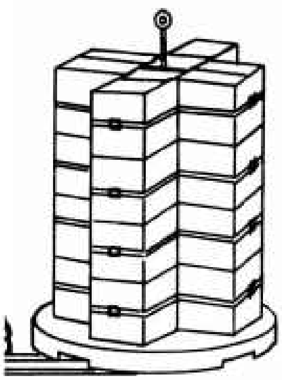




Clustered pallet load weighing
about 10,000 lbs.



with forty 40-mm ammunition
about 5700 lbs.

B. INVESTIGATION OF CARGO HOOK DESIGN PRINCIPLES

In our study, we found that hook failures did not occur often. However, the hook is the apex of the mechanical external cargo system, has no redundancy, and is the most unforgiving operational component, in that its failure almost always causes external cargo system failures. For these reasons, it is critical that cargo hook reliability be as great as is practically possible.

Elements of our investigation tend to suggest that there are certain basic but tractable design weaknesses resulting in unreliability in current hooks. For one thing a reasonable diversity of design principles was not evident in their development, as is typical with most design-optimized products. Secondly, the two principal types of hooks – electromechanical and hydraulic – experienced completely different causes of failures. This suggested that a combination of the best features of each would result in a superior hook design.

It has been suggested that design-weakness-caused unreliability has, in part, been perpetuated by MIL specifications and/or competitive economic constraints. It also may have been simply caused by the failure of designers to identify superior design principles. Most probably, it may have been caused by a poor matching of design features to requirements.

To analyze the possibility of superior designs, the cargo hook should be treated not as a separate component but as part of a system. The overriding requirement that the air crew has the capability of quickly jettisoning the load is all-persuasive. Therefore, provisions for air crew manipulation are as important as the strictly mechanical design of the hook. Operational redundancy tends to be precluded as too slow. It becomes extremely important that the manual controls operate in a predictable, unconfusing, and inadvertent operation-precluding manner.

Greater mechanical reliability can be achieved by a better matching of design characteristics employed to requirements or by simply making a mechanism stronger. In the latter case, increased reliability is bought at a price which may include greater size, weight, cost, or decreased speed. However, in the former instance – better matching – increased reliability can often be achieved without a significant penalty.

Optimal effectiveness then always infers a matching of requirements to design characteristics. Moreover, it entails a search for candidates and a trade-off analysis to identify an optimal candidate to requirement match. This then is the intended content of our proposed program.

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1. Objective

The objective of our proposed program would be:

- to make an interrelated, comprehensive analysis of requirements, specifications, history of design development, and the competitive-economic aspects of manufacturing cargo hooks;

- to identify apparent inadequacies in current designs;

- to generate a reasonable spectrum of new design concepts having the potential of overcoming the inadequacies identified;

- finally, by comparing this history with requirements, answer these questions:

  - How optimally reliable are the design principles employed in current cargo hook systems?

  - What, if any, are the constraining factors impeding more reliable basic designs?

  - What, if any, are potentially more reliable basic design concepts?

2. Scope of Work

The scope of work of the proposed program consists of eight principal tasks. These tasks and their interrelationships are shown in Figure 28. Their descriptions are as follows:

I. Historical Analysis

Review the history of cargo hook development. Identify the earliest mechanisms used for the hook itself and how they were integrated into a system. Identify the design principles, use factors, materials, and areas of inadequate performance.

Trace the development of these systems up to the present design, and identify pivotal changes and resultant changes in performance effected.

II. Requirements Analysis

Identify, in broad terms, the system requirements of the pilots and air crew in terms of release speed, control functions, indicator lights, etc. These requirements will also, of necessity, concern ease of making connections and load and release capacity and load dynamic requirements. In addition, delineate the environmental factors the hook system must withstand.

Many of the aforementioned parameters may not be completely quantifiable from the data. In these cases the investigator should attempt to design a series of tests to secure the required data. The data from these tests may also be augmented by data gathered by consensus. In fact, test and consensus data may be coupled to advantage.

III. Analysis of Specifications

Analyze current applicable specifications to detect how they have influenced or constrained designs. Of principal importance, delineate the performance, size/weight, and environmental resistance parameters.

Of greatest importance, assess the results of principal constraints by identifying such basic factors as size, weight, speed of operation, materials, etc. Arrayed against these parameters, identify concurrent results such as high-speed operation reducing reliability, greater size, and weight, etc.

IV. Analysis of Current Designs

Conduct a detailed analysis of current designs, identifying operating design principles, materials, and human factors. In comparison with Tasks II and III, the requirement analysis and analysis of specifications, respectively, assess where current specifications are not being met or are being exceeded and what are the apparent results of these variances.

V. Generate New Design Concepts

Develop a reasonably exhaustive number of concepts consistent with the requirements and other components of possible applicability, including such possibilities as a ball and socket, a magnetic device, and a shear strip arrangement, etc.

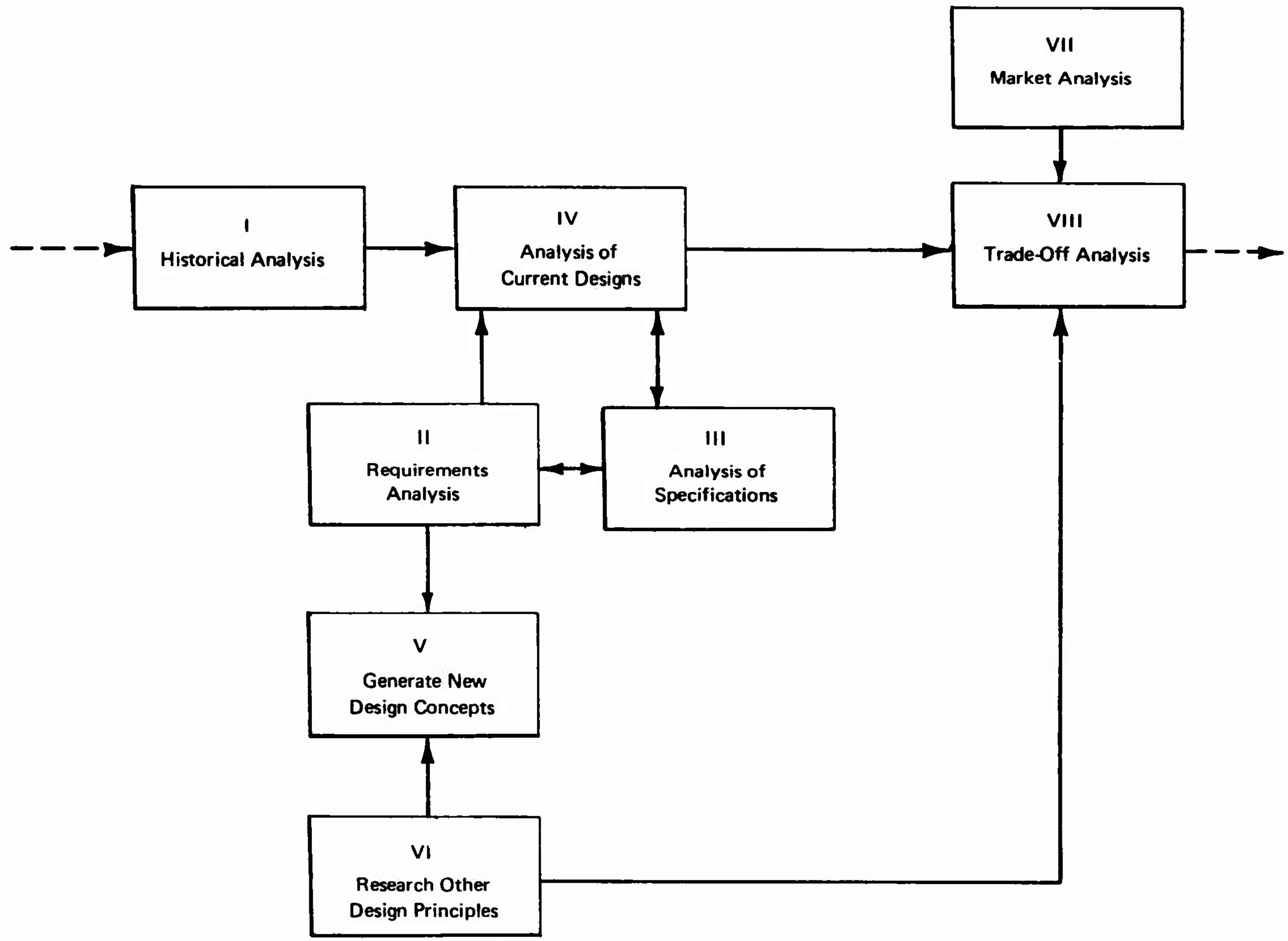

FIGURE 28. BLOCK DIAGRAM OF A PROPOSED PROGRAM TO INVESTIGATE CARGO HOOK DESIGN PRINCIPLES.

VI. Research Other Design Principles

Research other design principles on the basis that other components that embrace proven design principles might be superior to those used in current cargo hooks. Components that come to mind include bomb release mechanisms and the hooks used on commercial cargo cranes. Thus, search for components that have the same basic characteristics of cargo hooks; viz.,

- Quick, remotely actuated release of large loads,
- Compact and light weight, and
- High reliability.

This may very well lead one to components of completely different application such as hydraulic line disconnects. However, investigation of these areas may prove to be most fruitful.

VII. Market Analysis

Assess the market for cargo hooks over the years (particularly from 1960 to date) to determine just how cargo hook demand may have constrained development. We propose a market study not unlike one a manufacturer might undertake in considering a new market. It would, however, be substantially less detailed. One needs to know:

- Rough estimate of the dollar volume of the market,
- Number of competitors,
- Numbers of units produced and lot size estimates,
- Extent of government-supported R&D programs.

VIII. Trade-Off Analysis

Using standard techniques, compose all the factors generated in Tasks I through VII to answer the three basic questions posed in the "objective statement."

APPENDIX
SOURCES OF DATA

A. UNITS OF PILOTS AND AIR CREWMEN INTERVIEWED

- 355th Heavy Lift Company
  Ft. Eustis, Va.

- Maintenance School
  Ft. Eustis, Va.

- The T. School (Rigging)
  Ft. Eustis, Va.

- The Graduate Training School
  Ft. Rucker, Ala.

- 1st Cavalry Division – Delta Company
  Ft. Hood, Texas

- 178th Aviation Company
  Ft. Sill, Oklahoma

- The Marine Corps' Special Squadron
  Quantico, Va.

B. GOVERNMENT AGENCIES CONTACTED

- Office of Development, Director or Army Aviation
  Washington, D.C.

- U.S. Army Natick Laboratories
  Natick, Mass.

- U.S. Army Agency for Aviation Safety (USAAVS)
  Ft. Rucker, Ala.

- U.S. Army Materials Systems Analysis Agency (AMSAA)
  Aberdeen, Md.

- U.S. Naval Safety Center
  Norfolk, Va.

- U.S. Army Aviation Systems Command (USAAVSCOM)
  St. Louis, Mo.

- Logistics Branch, 1st Cavalry Division
  Ft. Hood, Texas

- U.S. Army Aviation Test Board
  Ft. Rucker, Ala.

- U.S. Army Combat Developments Command
  Ft. Rucker, Ala., and Ft. Eustis, Va.

- U.S. Navy Aerospace Recovery Facility
  El Centro, Calif.

- Marine Corps, Operational Analysis Group
  Roslyn, Va.

- Historical Section, Headquarters Marine Corps
  Washington, D.C.

C. COMMERCIAL HELICOPTER ASSOCIATIONS AND OPERATORS CONTACTED

- The Helicopter Association of America
  Washington, D.C.

- Petroleum Helicopters Inc.
  New Orleans, La.

- Western Helicopters Inc.
  Rialto, Calif.

- Keystone Helicopter Corp.
  Philadelphia, Pa.

- Evergreen Helicopters, Inc.
  McMinnville, Oregon

- Briles Wing and Helicopter Inc.
  Santa Monica, Calif.

- Erickson Lumber Co.
  Marysville, Calif.

D. MANUFACTURERS CONTACTED

- Boeing-Vertol Division
  Philadelphia, Pa.

- Sikorsky Aircraft Division
  Stratford, Conn.

- Bell Helicopter Co.
  Hurst, Texas

- Eastern Rotorcraft Corp.
  Doylestown, Pa.

- Aeroquip Corporation
  Jackson, Michigan

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